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WEDGWOOD PYROMETER.

HIGH-TEMPERATURE MEASUREMENTS.

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THE measurement of high temperatures was considered for a long time to be a very difficult operation and of a very uncertain precision. There were cited with admiration a half-dozen determinations seeming to merit some confidence. During the last few years the question has made considerable progress, and we possess to-day several sufficiently precise pyrometers whose usage is rapidly spreading among scientific and industrial laboratories. Before describing them, perhaps it will not be useless to indicate the services that they may render to science and to industry, by giving a brief summary of similar services that they have already rendered.

Among the researches in pure science which result from the new methods of the measurement of high temperatures, of primary importance are the masterly investigations of Osmond on the allotropic transformations of iron. After having precisely determined the nature of the phenomenon of recalescence, noted for the first time by Gore and Bartlett, Osmond discovered in iron two similar transformations: one, taking place in the neighborhood of 750°, corresponds to the loss of magnetic properties, and the other, at about 900°, is accompanied by a considerable evolution of heat. A third transformation of iron near 1300° has been discovered since by Ball. Soon after, Curie studied by the same methods the variation with the temperature of the magnetic properties of a great number

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of substances, iron among them, which possess very definite perturbations corresponding to the different transformation-points.

Later, Le Chatelier studied the influence of temperature on the dilatation and electrical resistance of metals. The allotropic transformations are recognized by sharp points in the curves of electrical resistance and by sudden depressions in the dilatation curves.

But these researches have not been limited to the metals and their alloys. Investigating the dilatation of the different varieties of silica, Le Chatelier was led to the discovery of a transformation of quartz at 580°, above which the dilatation of this substance becomes negative, and to the discovery, still more important, of a new variety of silica distinct from tridymite, but possessing the same density and into which silex and even quartz are transformed by sufficient heating.

In the same manner have been studied the dissociation of the carbonate of lime, the bromide of barium, of minium, etc. Similarly the curves of fusibility of salt mixtures have been determined, their forms indicating the existence of definite compounds or of solid solutions. Also it has been possible to distinguish, among the natural products classed under the general head clay, a series of distinct chemical substances.

Finally, it has been possible to pursue the study of the laws of radiation at high temperatures with a greater precision, and to establish the theory of incandescent enclosures.

If we take up next the researches in industrial science, we find the number to be so considerable that it is out of the question to attempt to give in this short preface the complete list. It will suffice to mention the most important among them, such as the following investigations:

The fusibility of metallic alloys has been the object of a very complete memoir by H. Gautier, and of important researches by Sir Roberts Austin and by Heycock and Neville.

The tempering of steel has been examined in all its details by Osmond, Charpy, H. Howe, Sauveur, Brinnel.

Cementation by Arnold.

Crystallization in the annealing of metals, in particular of iron and brass, observed by Sauveur, Stead, Charpy.

And lastly the considerable number of researches made at the laboratory of the Ecole des Mines on the dilatation of ceramic pastes and of glass, by Damour, Chatenet, Grenet, Coupeau, Chautepié.

But the use of precise methods for the measurement of high temperatures is not limited to laboratory researches. It has rapidly penetrated into industrial practice. A series of investigations by Le Chatelier first made known the exact temperatures entering into the various metallurgical operations; and to-day, in the greater number of steel-works, the tempering and the annealing of the great forged pieces, cannons, plates, are no longer made without the aid of pyrometers, doing away with the workman's judgment, formerly alone consulted.

In glass manufacture Damour has introduced the employment of pyrometers for controlling the large furnaces and recipients, and for the regulating of the temperature of the annealing-chambers.

Parvillé has done the same for the porcelain industry, where the use of fusible cones allowed the determination of the stopping-point of the heating but gave no continuous indications necessary to regulate the time of heating, and on this last depends in a large measure the quality of the products obtained, and above all the cost of fuel.

In the manufacture of chemical products the precise

measurements of temperature render to-day very great services; for instance, in the Deacon process for the making of chlorine, whose yield varies very greatly for slight changes of temperature. Ludwig Mond in England and the St. Gobian Company in France have the merit of having first utilized these new scientific methods.

Euchène of the Paris Gas Company controlled all the details of the manufacture of gas by numerous measurements of temperature.

But the most remarkable of these industrial applications have been made in England under the lead of Sir Roberts Austin by applying photographic recording to the indications of the thermoelectric pyrometer. Such installations at the Clarence Works of Sir Lothian Bell and at the blast-furnaces of Dowlais give a continuous record of the temperature of the draft and of the escaping gases.

These very considerable results have been obtained within less than ten years, although the new methods of temperature measurement were known as yet to only a few savants and engineers. It is plausible to suppose that their influence on the progress of science and industry will be still greater during the coming years.

In finishing this preface, allow me to thank Mr. G. K. Burgess for having taken the trouble to translate into English our little volume. His science and his competence are for us a certain guarantee of cordial reception by American and English readers.

H. Le Chatelier.

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HIGH TEMPERATURES.

INTRODUCTION.

WEDGWOOD, the celebrated potter of Staffordshire, the inventor of fine earthenware and of fine china, was the first to occupy himself with the exact estimation of high temperatures. In an article published in 1782, in order to emphasize the importance of this question, he considers at length certain matters a study of which would be well worth while even to-day.

" The greater part of the products obtained by the action of fire have their beauty and their value considerably depreciated by the excess or lack of very small quantities of heat; often the artist can reap no benefit from his own experiments on account of the impossibility to duplicate the degree of heat which he has obtained before his eyes. Still less can he profit from the experiments of others, because it is even less easy to communicate the imperfect idea which each person makes for himself of these degrees of temperature."

Joining example to precept, Wedgwood made for his personal use a pyrometer utilizing the contraction of clay. This instrument, for nearly a century, was the only guide in researches at high temperatures. Replaced to-day by

apparatus of a more scientific nature, it has been perhaps too readily forgotten.

Since Wedgwood, many have undertaken the measurement of high temperatures, but with varying success. Too indifferent to practical requirements, they have above all regarded the problem as a pretext for learned dissertations. The novelty and the originality of methods attracted them more than the precision of the results or the facility of the measurements. Also, up to the past few years, the confusion has been on the increase. The temperature of a steel kiln varied according to the different observers from 1500° to 2000°; that of the sun from 1500° to 1,000,000°.

First of all, let us point out the chief difficulty of the problem. Temperature is not a measurable quantity in the strict sense of the term. To measure a length or a mass, is to count how many times it is necessary to take a given body chosen as a unit (meter, gramme) in order to obtain a complex system equivalent either as to length or mass of the body in question. The possibility of such a measurement presupposes the previous existence of two physical laws: that of equivalence, and that of addition. Temperature obeys well the first of these laws; two bodies in temperature equilibrium with a third, and thus equivalent with respect to exchanges of heat in comparison with this third body, will also be equivalent, that is to say, equally in equilibrium with respect to every other body which would be separately in equilibrium with one of them. This law allows determination of temperature by comparison with a substance arbitrarily chosen as thermometric body. But the second law is wanting; one cannot, by the juxtaposition of several bodies at the same temperature, realize a system equivalent, from the point of view of exchanges of heat, to a body of different temperature

thus temperature is not measured, at least insomuch as one considers only the phenomena of convection.

In order to determine a temperature, one observes any phenomenon whatever varying with change of temperature. Thus for the mercury centigrade thermometer the temperature is defined by the *apparent expansion of mercury* from the *point of fusion of ice* measured by means of a unit equal to $\frac{1}{100}$ of the dilatation between the temperature of the *fusion of ice and that of the ebullition of water* under atmospheric pressure.

Thermometric Scales.—For such a determination there are four quantities to be chosen arbitrarily: the *phenomenon* measured, the thermometric *substance,* the *origin* of graduation, and the *unit* of measurement; while in a measurement properly so called there is but one quantity to be arbitrarily chosen, the magnitude selected as unity. It is evident that the number of thermometric scales may be indefinitely great; too often experimenters have considered it a matter of pride for each to have his own.

Here are some examples of thermometric scales chosen from among many:

Author.	Phenomenon.	Substance.	Origin.	Unit.
Fahrenheit	Dilatation	Mercury	{ Very cold winter	} 1/180 Ice to B. P.
Réaumur	"	"	Ice	1/80 " " "
Celsius	"	"	"	1/100 " " "
Wedgwood	{ Permanent contraction }	Clay	Dehydrated	1/2400 init. dimens.
Pouillet	Dilat. at const. p.	Air	Ice	
(Normal ther.)	Dilat. at const. v.	Hydrogen	"	1/100
(Thermodyn. scale)	{ Reversible heat-scale }	Anything	Heat = 0	Ice to boiling-point
Siemens	Electric resistance	Platinum	Ice	

The enormous differences above mentioned in the measurements of high temperatures are much more the

result of the diversity of the scales than due to the errors of the measurements themselves. Thus the experiments on solar radiation which have led to values varying from 1500° to 1,000,000° are based on measurements which do not differ among themselves by more than 25 per cent.

To escape from this confusion it was first necessary to agree upon a single scale of temperatures; that of the gas-thermometer is to-day universally adopted, and this choice may be considered as permanent. The gases possess, more than any other state of matter, a property very important for a thermometric substance—the possibility of being reproduced at any time and in any place identical with themselves; besides, their dilatation, which defines the scale of temperatures, is sufficient for very precise measurements; finally, this scale is practically identical with the thermodynamic scale. This last is in theory more important than all the other properties because it is independent of the nature of the phenomena and of the substances employed. It gives, too, a veritable measure and not a simple comparison; its only inconvenience is for the moment not to be experimentally realizable, at least rigorously, but it is impossible to say if this will always be the case.

The adoption of the scale of the gas-thermometer does not in any way imply the obligation to use this instrument actually in all measurements. One can take any thermometer, provided that in the first place its particular scale has been standardized by comparing it with that of the gas-thermometer. According to the case, there will be advantage in employing one or another method; practically also one almost never employs the gas-thermometer by reason of the difficulties inherent in its use, which result principally from its great dimensions and of its fragility.

It is our purpose, in this introduction, to pass in review

rapidly the different pyrometric methods (that is to say, thermometers utilizable at high temperatures) whose employment may be advantageous in one or another circumstance; we shall then describe more in detail each of them, and shall discuss the conditions for their employment. But in the first place it is necessary to define within what limits the different scales may be compared to that of the normal gas-thermometer; it is the insufficiency of this comparison which is still to-day the cause of the most important errors in the measurement of high temperatures.

Fixed Points.—The standardization of the different pyrometers is the most frequently made by means of the fixed points of fusion and ebullition which have been determined in the first place by means of the gas-thermometer; the actual precision of the measurements of high temperatures is entirely subordinate to that with which these fixed points are known; this precision is not very great because these fixed points have only been compared in an indirect manner with the gas-thermometer, and some of them only by aid of processes of extrapolation, always very uncertain.

Violle was the first to make a series of experiments of considerable precision, which up to these last few years were our only reliable data on the question. In a first series of researches he determined the specific heat of platinum by direct comparison with the air-thermometer between the temperatures of 500° and 1200°. He made use indirectly of the relation thus established between specific heat and temperature to determine by comparison with platinum the points of fusion of gold and silver; then, by extrapolation of this same relation, the points of fusion of palladium and of platinum.

	Ag	Au	Pd	Pt
Fusion............	954°	1045°	1500°	1779°

Finally, in a second series of experiments, he determined by direct comparison with the air-thermometer the boiling-point of zinc.

$$\text{Boiling-point} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \begin{cases} \text{Zn} \\ 929.6 \end{cases}$$

Barus, chemist of the United States Geological Survey, has determined the boiling-points of several metals by means of thermoelectric couples standardized against the air-thermometer.

	Cd	Zn
Boiling-point.......... {	772° and 784°	926° and 931°
Mean.............	778°	928°.5

Callendar and Griffiths, by means of a platinum resistance-thermometer calibrated up to 500° by comparison with the air-thermometer, have determined the following points of fusion and ebullition:

	Sn	Bi	Cd	Pb	Zn
Fusion......... {	232°	270°	322°	329°	421°

	Aniline	Napthaline	Benzophenone	Mercury	Sulphur
Boiling-point under 760 mm. {	184°.1	217°.8	305°.8	356°.7	444°.5

These last figures may be compared with Regnault's and Crafts' previous determinations:

Naphthaline	Benzophenone	Mercury	Sulphur
218°	306°.1	357°	445°

Heycock and Neville, employing the same method, but with extrapolation of the law of resistance for platinum, established only up to 450°, have determined the following points of fusion:

Sn	Zn	Mg (99.5%)	Sb	Al (99%)	Ag	Au	Cu
232°	419°	633°	629°.5	654°.5	960°.5	1062°	1080°.5

Finally, Holborn and Wien of the Physikalische Reichsanstalt of Berlin, have recently made a series of determinations, which seem, of all those made up to this time, to merit the greatest confidence. They have determined the

points of fusion by means a thermocouple compared up to 1400° with the air-thermometer.

Fusion (mean). .... {	Ag	Au	Pd	Pt
	970°	1072°	1580°	1780°

Mr. Daniel Berthelot, by quite recent experiments, has calibrated a thermocouple by comparison with the gas-thermometer, making use of the variation of the indices of refraction with the density. With this thermocouple he has determined the points of fusion:

{	Ag	Au
{	962°	1064°

From this collection of results we may conclude that the fixed points presenting actually the greatest reliability for the indirect standardization of the various thermometric scales are the following:

	Sn	Naphthaline	Zn	S	Sb	Al	Zn	Ag	Au	Pt
Fusion....	232°	—	420°	—	630°	655°	—	962°	1065°	1780°
Ebullition.	—	218°	—	445°	—	—	930°	—	—	—

We may consider these temperatures as known with an uncertainty inferior to:

1°..............................	between 200° and 500°
5	" 500 " 800
10	" 800 " 1100
50	above 1100

In spite of the concordance between the two determinations of the fusing-point of platinum, one must entertain certain doubts of the precision of the number obtained; it results in the two cases from extreme extrapolations whose concordance may be fortuitous.

Pyrometers.—Among the many proposed pyrometric methods, we shall dwell upon the following, the only ones which up to the present have been seriously employed.

Gas-pyrometer (Pouillet, Becquerel, Sainte-Claire-De-ville).—Utilizes the measurement of change in pressure of

a gaseous mass kept at constant volume. Its great volume and its fragility render it unsuitable for ordinary measurements; it serves only to give the definition of temperature and should only be used to standardize other pyrometers.

Calorimetric Pyrometer (Regnault, Violle, Le Chatelier). —Utilizes the total heat of metals (platinum in the laboratory and nickel in industrial works). Is to be recommended for intermittent researches in industrial establishments because its employment demands almost no apprenticeship and because the cost of installation is not great.

Radiation Pyrometer (Rosetti, Langley, Boys).—Utilizes the total heat radiated by warm bodies. Its indications are influenced by the variable emissive power of the different substances. Convenient for the evaluation of very high temperatures which no thermometric substance can withstand (electric arc, sun).

Optical Pyrometer (Becquerel, Le Chatelier).—Utilizes the photometric measurement of radiation of a given wavelength of a portion of the visible spectrum. Its indications, as in the preceding case, are influenced by variations in emissive power. The intervention of the eye aids greatly the observations, but diminishes notably their precision. This method is mainly employed in industrial works for the determination of the temperatures of bodies difficult of access—for example, of bodies in movement (the casting of a metal, the hot metal passing to the rolling-mill).

Electric-resistance Pyrometer (Siemens, Callendar.)— Utilizes the variations of electric resistance of metals (platinum) with the temperature. This method permits of very precise measurements, but requires the employment of fragile and cumbersome apparatus. It will merit the preference for very precise investigations in laboratories when we have a satisfactory determination of the variation

of resistance of platinum in terms of the normal gas-thermometer.

Thermoelectric Pyrometer (Becquerel, Barus, Le Chatelier).—Utilizes the measure of electromotive forces developed by the difference in temperature of two similar thermoelectric junctions opposed one to the other. In employing for this measurement a Deprez-d'Arsonval galvanometer with movable coil, one has an apparatus easy to handle and of a precision amply sufficient considering the actual state of the means of standardization at our disposal in terms of the normal scale of temperature. This pyrometer is more generally used in scientific laboratories than in industrial works.

Contraction Pyrometer (Wedgwood).—Utilizes the permanent contraction that clayey materials take up when submitted to temperatures more or less high. It is employed to-day only in a few pottery works.

Fusible Cones (Leger).—Utilizes the unequal fusibility of earthenware blocks of varied composition. Gives only discontinuous indications. Such blocks studied by Leger are spaced so as to have fusing-points distant about 20°. In general use in pottery works and in some similar industries.

CHAPTER I.

NORMAL SCALE OF TEMPERATURES.

We have seen that temperature is not a measurable quantity; it is merely comparable with respect to a scale arbitrarily chosen.

The normal scale is the *thermodynamic scale;* but as it is impossible to realize rigorously this scale, it is necessary to have a practical one. In the same way that, besides the theoretical definition of the meter, there is a practical standard, a certain meter kept at the Bureau International des Poids et Mesures, there exists, besides the normal scale of temperatures, a practical scale which is a certain gas-thermometer which we are going to study.

Laws of Mariotte and Gay-Lussac.—The laws of Mariotte and Gay-Lussac are the basis for the use of the dilalation of gases for the determination of temperatures. These two laws may be written

$$\frac{p_1 v_1}{p_0 v_0} = \frac{1 + \alpha t_1}{1 + \alpha t_0}, \quad \cdots \quad (1)$$

the temperatures being measured with the mercury-thermometer. α is a numerical coefficient, the same for all gases, at least to a first approximation, and its value is

$$\alpha = 0.00366 = \tfrac{1}{273}$$

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when it is agreed that the interval between the temperatures of melting ice and boiling water is 100°.

But instead of considering the formula (1) as the expression of an experimental law joining the product *pv* to the temperature defined by the mercury-thermometer, we may require of experiment merely the law of Mariotte and write *à priori* the formula in question, giving a new definition of temperature approximating that of the mercury-thermometer. This new scale has the advantage that it adapts itself to the study of very much higher temperatures. The use of this process suggested by Pouillet was carefully studied by Regnault.

The expression for the laws of Mariotte and Gay-Lussac can be put in the form

$$pv = nR\left(\frac{1}{\alpha} + t\right) \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (2)$$

by calling *n* the number of units of quantity (this unit may be either the molecular weight or the gramme); *R* the value of the expression

$$\frac{p_0 v_0}{\frac{1}{\alpha} + t_0}$$

for unit quantity of matter taken at the temperature of melting ice and under atmospheric pressure.

Gas-thermometers.—The equivalent expressions (1) and (2), which arbitrarily by convention give the definition of temperature, can be utilized, from the experimental point of view, in various ways for the realization of the normal thermometer.

1. *Constant-volume Thermometer.*—In the thermometer designated by this name the volume and the mass are kept invariable.

The expression (2) then gives between the two temperatures t and t_0 the relation

$$\frac{p}{p_0} = \frac{1}{\alpha} + t_0,$$

from which

$$t - t_0 = p - p_0\left(\frac{1}{\alpha} + t_0\right). \quad . \quad . \quad . \quad . \quad (3)$$

2. *Constant-pressure Thermometer.*—In this case the pressure and the volume of the heated mass remain constant, but the mass is variable; a part of the gas leaves the reservoir. The expression (2) then gives

$$1 = \frac{n}{n_0} \cdot \frac{\dfrac{1}{\alpha} + t}{\dfrac{1}{\alpha} + t_0},$$

from which

$$t - t_0 = \frac{n_0 - n}{n_0}\left(\frac{1}{\alpha} + t\right). \quad . \quad . \quad . \quad (4)$$

It would be much more logical, instead of the classic expressions constant-volume thermometer or constant-pressure thermometer, to say *thermometer of variable pressure, thermometer of variable mass,* which describe much more exactly the manner of their action.

3. *Thermometer of Variable Pressure and Mass.*—The action of this apparatus combines those of the two preceding types. A part of the gas leaves the reservoir, and the pressure is not kept constant. The expression (2) gives

$$\frac{p}{p_0} = \frac{n}{n_0} \cdot \frac{\dfrac{1}{\alpha} + t}{\dfrac{1}{\alpha} + t_0},$$

from which

$$t - t_0 = \frac{pn_0 - p_0 n}{p_0 n} \cdot \left(\frac{1}{\alpha} + t_0\right). \quad \cdot \quad \cdot \quad \cdot \quad (5)$$

4. *Volumetric Thermometer.* — There exists a fourth method of the use of the gas-thermometer which was suggested by Ed. Becquerel, and presents, as we shall see later, a particular interest for the evaluation of high temperatures. We keep the name for it given by its inventor. The determination of the temperature is obtained by two measurements made at the same temperature, and not as in the preceding methods by two measurements made at two different temperatures one of which is supposed known. The mass contained in the reservoir is varied, and the ensuing change of pressure is observed. The expression (2) gives

$$pv = nR\left(\frac{1}{\alpha} + t\right),$$

$$p'v = n'R\left(\frac{1}{\alpha} + t\right),$$

from which

$$(p - p')v = (n - n')R\left(\frac{1}{\alpha} + t\right),$$

or

$$t = -\frac{1}{\alpha} + \frac{p - p'}{n - n'} \cdot \frac{v}{R}. \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (6)$$

This necessitates a preliminary determination of the constant R.

In the particular case in which $p' = 0$, which supposes that a complete vacuum is obtained, the preceding relation becomes simpler and is

$$t = -\frac{1}{\alpha} + \frac{p}{n} \cdot \frac{v}{R}. \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (7)$$

The definitions of temperature given by these different thermometers would be equivalent among themselves and with that of the mercury-thermometer if the laws of Mariotte and Gay-Lussac were rigorously exact, as used to be held. The only advantage of the gas-thermometer in that case would be to extend to high temperatures the scale of the mercury-thermometer. In this way it was employed by Pouillet, Becquerel, Sainte-Claire-Deville.

Experiments of Regnault.—The very precise experiments of Regnault caused a modification in the then admitted ideas concerning the mercury-thermometer as well as the gas-thermometer, and have led to the definite adoption of a normal gas-thermometer.

In the first place these experiments established that different mercury-thermometers are not comparable among themselves on account of the unequal dilatation of the differing glass employed in their construction. Thus they cannot give an invariable scale for the determination of temperature. In comparing them from 0° to 100° they do not present between these extreme temperatures very great differences, 0°.30 as a maximum, but at temperatures above 100° these differences may become considerable and reach 10°.

Constant-vol. Air-thermometer, $p_0 = 760$.	Mercury-thermometer in			
	Crystal.	White Glass.	Green Glass.	Bohemian Glass.
100°	+ 0°.00	+ 0°.00	+ 0°.00	+ 0°.00
150	+ 0 .40	− 0 .20	+ 0 .30	+ 0 .15
200	+ 1 .25	− 0 .30	+ 0 .80	+ 0 .50
250	+ 3 .00	+ 0 .05	+ 1 .85	+ 1 .44
300	+ 5 .72	+ 1 .08	+ 3 .50	
350	+ 10 .50	+ 4 .00		

The numbers figuring in this table indicate the quantities by which it is necessary to increase or diminish the temperatures given by the air-thermometer in order to

have them correspond with those which were observed with the different mercury-thermometers.

It was thus impossible to define the practical scale of temperatures in terms of the mercury-thermometer. The use of the gas-thermometer became necessary. But Regnault recognized that it was not possible to take a *single coefficient of dilatation* α, independent of the *nature* of the gas, of its *pressure*, and of the *mode of dilatation* utilized. The coefficient of expansion at constant volume (α) and the coefficient of expansion at constant pressure (β) are not identical. This follows from the fact that the law of Mariotte is not rigorously exact; we have in reality

$$pv = p_0v_0 + \epsilon,$$

ϵ being a very small quantity, but not zero.

The experiments of Regnault permitted him not only to detect but to measure this variation of the coefficient of expansion. Here are, for example, the results which he found for air between 0° and 100°:

Volume Constant.			Pressure Constant.		
Pressure.	α	$\frac{1}{\alpha}$	Pressure.	β	$\frac{1}{\beta}$
266	0.003656	273.6	760	0.003671	272.4
760	3655	272.8	2525	3694	270.7
1692	3689	271	2620	3696	270.4
3655	3709	269.5			

For air at 4°.5 Rankine obtains, from the experiments of Regnault, the formula

$$pv = p_0v_0 + 0.008163\frac{p - p_0}{\omega} \cdot pv,$$

ω being the atmospheric pressure.

These coefficients vary also from one gas to another, as is shown by the following table, taken also from Regnault's experiments:

MEAN COEFFICIENT BETWEEN 0° AND 100°.

Volume Constant.			Pressure Constant.		
Pressure. mm.	a	$\frac{1}{a}$	Pressure. mm.	β	$\frac{1}{\beta}$
AIR.					
760	0.003665	272.8	760	0.003671	272.4
3655	3708	269.5	2620	3696	270.4
HYDROGEN.					
760	3667	272.7	760	36613	273.1
			2545	36616	273.2
CARBON MONOXIDE.					
760	3667	272.7	760	3669	272.5
NITROGEN.					
760	3668	272.6			
CARBONIC ACID.					
760	3688	271.2	760	3710	269.5
3589	3860	259	2520	3845	259.5
SULPHUROUS ACID.					
760	3845	259.5	760	3902	253.0
			980	3980	251.3

These experiments show that the easily liquefiable gases have coefficients quite different from those of the permanent gases.

For the permanent gases the coefficients for constant volume differ much less among themselves than those for constant pressure; for the former the extreme deviation does not exceed $\frac{1}{1000}$, for the latter it is three times as great. Setting aside air, which is a mixture and which contains more easily liquefiable oxygen, the coefficients for constant volume of H_2, N_2, and CO are identical.

Finally, for hydrogen the coefficient of expansion does not vary with the pressure.

The inequality of the coefficients of expansion, however, does not prevent us from taking any gas whatever to define the scale of temperature, provided we apply to it the proper coefficient determined by experiment between

0° and 100°. The scales are identical, if the coefficients of expansion do not vary with the temperature. This is the conclusion to which Regnault came from a comparison of thermometers at constant volume, differing by their initial pressure or the nature of the gas. Here are the results obtained, starting from the fixed points 0° and 100°, by the aid of the following formulæ:

$$pv = nRT,$$

$$p_0v = nRT_0,$$

$$p_{100}v = nRT_{100},$$

$$\frac{p - p_0}{p_{100} - p_0} = \frac{T - T_0}{T_{100} - T_0} = \frac{t}{100}.$$

AIR-THERMOMETER.

$p_0 = 751$ mm.	$p_0 = 1486$ mm.
Degrees.	Degrees.
156.18	156.19
259.50	259.41
324.33	324.20

PRESSURE = 760 MILLIMETERS.

Air-thermometer.	Hydrogen-thermometer.	Air-thermometer.	CO_2-Thermometer.
Degrees.	Degrees.	Degrees.	Degrees.
141.75	141.91	159.78	160.00
228.87	228.88	267.35	267.45
325.40	325.21	322.8	322.9

The deviations do not exceed 0°.2, a value that Regnault estimated not to exceed the limits of error of his experiments; he concluded from this that one gas may be used as well as another, and he took air for the normal thermometer.

Nevertheless his experiments on sulphurous acid had shown a very marked variation of the coefficient of expansion of this gas with the temperature. The following

table gives the mean coefficient at constant volume between $0°$ and $t°$:

t	a
98.0	0.0038251
102.45	38225
185.42	37999
257.17	37923
299.90	37913
310.31	37893

By analogy it is permissible to suppose that a similar effect should take place with the other gases; but the differences were then too small, and the degree of precision of the methods of Regnault insufficient to detect it.

This effect has been demonstrated by experiments of very great precision made at the Bureau International des Poids et Mesures, at Sèvres. Chappuis has found, between $0°$ and $100°$, systematic deviations between thermometers of hydrogen, nitrogen, and carbonic acid, filled at $0°$ under a pressure of 1000 mm. of mercury.

Hydrogen Ther.	N Ther. − H Ther.	N Ther. − CO_2 Ther.
− 15°	− 0°.016	− 0°.094
0	0	0
+ 25	+ 0 .011	+ 0 .050
+ 50	+ 0 .009	+ 0 .059
+ 75	+ 0 .011	+ 0 .038
+ 100	0	0

In this table, taking as definition of the temperature the hydrogen-thermometer at constant volume, the numbers in the last two columns indicate the deviations observed with the thermometers of nitrogen and carbonic acid; it is certain that these deviations are systematic. These results allow of the determination of the mean coefficients of expansion:

t	a (Hydrogen).	a (Nitrogen).	a (Carbonic Acid).
0°	....	0.00367698	0.00373538
100°	0.00366254	367466	372477

Thus the coefficients decrease with rise of temperature, while remaining higher than that of hydrogen, to which they tend to approach.

Normal Scale of Temperatures.—It results from these experiments that the different scales furnished by the various gas-thermometers are not rigorously identical; the deviations between 0° and 100° are very small, but their existence is certain. It becomes necessary, therefore, in order to have a *scale of temperature rigorously defined,* to make a choice of the *nature* of the gas, of its *manner of dilatation,* and of its initial *pressure.*

The *normal thermometer* selected by the Bureau International des Poids et Mesures to define the practical scale of temperatures, and everywhere adopted to-day, is the *hydrogen thermometer,* operated at constant volume and filled with gas at 1000 millimeters of mercury at the temperature of melting ice.

For high temperatures this definition is inadmissible, because we would reach such pressures that the apparatus could not withstand. The use of the method at constant volume, that is to say, at invariable mass, is besides bad on account of the permeability of the coverings at high temperatures. It would be of great advantage to be able to employ a gas other than hydrogen and operate the thermometer at variable mass.

In the actual state of experimentation at high temperatures, it is impossible to have results exact to about 1°, and indeed, practically, we are far from arriving at this precision. It is very likely that we can, under these conditions, employ indifferently for the construction of the normal thermometer any permanent gas whatsoever. According to the preceding experiments, all the gases would have a dilatation slightly greater than that for hydrogen, and their coefficient of expansion, which

decreases with rise of temperature, would approach that for hydrogen. For determining experimentally the error possible with a normal thermometer thus modified, we possess actually but little data.

Crafts has compared in the neighborhood of 1500° the expansion at constant pressure of nitrogen and carbonic acid, and found for this latter the mean coefficient 0.00368 in assuming 0.00367 for nitrogen.

The experiments were made by displacing in a Meyer's tube nitrogen by carbonic acid, or carbonic acid by nitrogen.

10 cc. N_2 displace	10 cc. CO_2 displace
10.03 of CO_2	9.95 of N_2
10.01	9.91
10.00	9.98
10.03	9.93
9.95	——
10.09	Mean 9.94
——	
Mean 10.02	

The two measurements give positive and negative differences of the same order of magnitude; but it should be noticed that the observed deviation ($\frac{4}{1000}$ on an average) hardly exceeds the possible error of observation. However it may be, carbonic acid, which differs much from the permanent gases at ordinary temperatures, no longer so differs in an appreciable degree at 1500°.

Violle has made some comparative measurements on the air-pyrometer used at constant pressure and constant volume in his determinations of the specific heat of platinum.

Vol. Constant.	Press. Constant.	Difference.
1171°	1165°	6°
1169	1166	3
1195	1192	3

There was on an average a deviation of only 4° between the two modes of observation, and the greater part of this

deviation should be laid to accidental variations of the gaseous mass resulting from the permeability of the coverings.

We can then affirm that, in employing any permanent gas with any mode of dilatation, we shall not differ certainly by more than 5° in 1000° from the temperature of the normal scale, and in reality the deviation will be without doubt much less, and should not reach 1°.

Theoretically it would be preferable to use hydrogen under reduced pressure, which would certainly not give deviations of 1° from the normal scale; but there is always the danger of the passage of this gas through the coverings, and of its combustion by oxygen or oxides.

Practically it would be better to take nitrogen, whose expansion deviates little from that of hydrogen, less than the deviation of air.

For high temperatures the normal thermometer will be, then, a nitrogen-thermometer.

Thermodynamic Scale.—It is defined, in terms of Carnot's principle applied to a reversible cycle working between two sources at constant temperatures, by the relation

$$\frac{L_1}{L_0} = \frac{T_1}{T_0}. \qquad \cdots \cdots \cdots (1)$$

1. *Approximate Expression.*—Consider Carnot's cycle formed, as is well known, of two isotherms and two adiabatics, and let us seek the quantity of heat absorbed following the isotherm T_1.

From Joule's experiments we have approximately

$$L_1 = A \int p\,dv.$$

The laws of Mariotte and Gay-Lussac give

$$pv = R\left(\frac{1}{\alpha} + t\right),$$

where t is the temperature of the gas-thermometer; then,

$$dv = - R\frac{dp}{p^2}\left(\frac{1}{\alpha} + t\right); \text{ and}$$

$$L_1 = - AR\left(\frac{1}{\alpha} + t_1\right) \cdot \int_{p_1'}^{p_1''}\frac{dp}{p} = AR\left(\frac{1}{\alpha} + t\right)\log\frac{p_1'}{p_1''}.$$

Similarly,

$$L_0 = AR\left(\frac{1}{\alpha} + t_0\right)\log\frac{p_0'}{p_0''}.$$

Equation (1) becomes

$$\frac{T_1}{T_0} = \frac{L_1}{L_0} = \frac{\dfrac{1}{\alpha} + t_1}{\dfrac{1}{\alpha} + t_0}\left(\log\frac{p_1'}{p_1''} - \log\frac{p_0'}{p_0''}\right). \qquad (2)$$

But the experiments on adiabatic expansion give

$$pv^\gamma = \text{const.},$$

and combining with the laws of Mariotte and Gay-Lussac,

$$p^{\gamma-1} \cdot t^{-\gamma} = \text{const.}$$

Consequently $\dfrac{p_1}{p_0}$ depends only on the ratio $\dfrac{t_1}{t_0}$, which is the same the whole length of the two isotherms. Thus

$$\frac{p_1'}{p_0'} = \frac{p_1''}{p_0''},$$

or

$$\frac{p_1'}{p_1''} = \frac{p_0'}{p_0''}.$$

Equation (2) then takes the very simple form

$$\frac{T_1}{T_0} = \frac{\dfrac{1}{\alpha} + t_1}{\dfrac{1}{\alpha} + t_0};$$

that is to say, the *ratio of the absolute thermodynamic temperatures is equal to the ratio of the absolute temperatures of the gas-thermometer;* and if in the two scales it is agreed to take equal to 100 the interval comprised between the temperatures of melting ice and the vapor of boiling water, we have, at any temperature, the equality

$$T = \frac{1}{\alpha} + t.$$

But this is only a first approximation, for we have employed relations that are but roughly so: the laws of Joule, Mariotte, and Gay-Lussac.

2. Reconsider the problem by a more exact method. Since T differs very little from $\dfrac{1}{\alpha + t}$, and since the laws of Mariotte and Gay-Lussac are nearly true, we place, following a method of calculation indicated by Callendar,

$$pv = RT(1 - \phi),$$

ϕ being a very small function of p and of T (thermodynamic temperature).

We have then, between the temperature of the gas-thermometer and the thermodynamic temperature, the relation

$$\frac{\dfrac{1}{\alpha} + t_1}{\dfrac{1}{\alpha} + t_0} = \frac{T_1(1 - \phi_1)}{T_0(1 - \phi_0)},$$

which will permit of passing from one scale of temperature to the other if we know the corresponding value of ϕ.

Consider, as before, Carnot's cycle, and let us determine the heat of isothermal expansion in a more exact manner, by utilizing the experiments of Joule and Thomson on the

expansion through a porous plug, and those of Regnault
on the deviations from Mariotte's law.

We write for this that the changes in energy between
two given isothermal states are the same, either for the
reversible expansion or for the expansion of Joule and
Thomson:

$$L_1 - A \int_{p_1'}^{p_1''} p\,dv = - A(p_1''v_1'' - p_1'v_1') + \int_{p_0'}^{p_1''} \frac{d\epsilon_1}{dp}dp,$$

ϵ being the very feeble change in heat of the gas accom-
panying its passage through the porous plug, in the ex-
periment of Joule and Thomson. We get from this

$$L_1 = A \int_{p_1'}^{p_1''} v\,dp + \int \frac{d\epsilon_1}{dp}dp \text{ (at constant temperature), (3)}$$

for

$$d(pv) = p\,dv + v\,dp.$$

The relation

$$pv = RT(1 - \phi)$$

gives for the value of v

$$v = \frac{RT}{p}(1 - \phi),$$

which, substituted in equation (3), leads to

$$L_1 = ART_1 \cdot \int_{p_1'}^{p_1''} \frac{dp}{p} - ART_1 \cdot \int \phi_1 \frac{dp}{p} + \int \frac{d\epsilon_1}{dp}dp. \quad (4)$$

Similarly, we have

$$L_0 = ART_0 \cdot \int_{p_0'}^{p_0''} \frac{dp}{p} - ART_0 \cdot \int \phi_0 \frac{dp}{p} + \int \frac{d\epsilon_0}{dp}dp. \quad (5)$$

If we introduce these values in the expression for Carnot's cycle, after division by T_1 and T_0 we should find an identity:

$$\frac{L_1}{T_1} - \frac{L_0}{T_0} = AR \, \log_e \frac{p_1''p_0'}{p_1'p_0''} - \int_{p_1'}^{p_1''} \left(AR\frac{\phi_1}{p} - \frac{1}{T_1} \cdot \frac{d\epsilon_1}{dp} \right) dp$$

$$+ \int_{p_0'}^{p_0''} \left(AR\frac{\phi_0}{p} - \frac{1}{T_0} \frac{d\epsilon_0}{dp} \right) dp = 0.$$

The law of adiabatic expansion gives

$$\frac{p_1''p_0'}{p_1'p_0''} = 1 \quad \log_e \frac{p_1''p_0'}{p_1'p_0''} = 0.$$

In order, then, that the expression reduce to an identity it is necessary that

$$\frac{1}{T} \cdot \frac{d\epsilon}{dp} = AR\frac{\phi}{p}, \quad \text{or} \quad \phi = \frac{d\epsilon}{dp} \cdot p \cdot \frac{1}{AR} \cdot \frac{1}{T}.$$

Referring to the experiments on air of Joule and Thomson, we have

$$\phi = 0.001173 \cdot \frac{p_1}{p_0} \cdot \left(\frac{T_0}{T_1} \right)^3,$$

p_0 being the atmospheric pressure, and T_0 the temperature of melting ice.

This is still an approximate result, for we have depended upon the experiments of Joule and Thomson and on the law of adiabatic expansion; however, the approximation is more close. If it seems sufficient for air, it is certainly not so for carbonic acid. Neither is the formula rigorously exact for air.

Callendar has calculated the correction to make to the air-thermometer readings by extrapolation up to 1000°, and he found the following results:

Readings of Centigrade Thermometer.	Volume Constant.		Pressure Constant.	
	ϕ	Δt	ϕ	Δt
0°	0.001173	0	0.001173	0
100	0.000627	0	0.000457	0
200	393	0.04	225	0.084
300	267	0.09	127	0.20
500	147	0.23	52	0.47
1000	54	0.62	12	1.19

The deviations of the air-thermometer at high temperatures are thus very slight if concordance is established at 0° and 100°; we shall not have to occupy ourselves further with the differences between the indications of the thermodynamic thermometer and those of the gas-thermometer.

It is possible to make use of these same experiments of Joule and Thomson to determine the absolute temperature of the fusion of ice on the thermodynamic scale.

Here are the results of the computation of Mr. Lehrfeldt; he gives the following corresponding readings of the gas-thermometer at constant volume and of the thermodynamic thermometer:

	Gas Ther.	Thermodyn Ther.
Hydrogen	273.08	272.8
Air	272.48	273.27
Nitrogen	273.13	273.2
Carbonic acid	268.47	$\begin{cases} 274.83 & \text{(Thomson)} \\ 373.48 & \text{(Natanson)} \end{cases}$

The thermodynamic temperature of melting ice should be in all cases the same; the deviations come from the uncertainties in the measurements of the heat of expansion. We should, according to these results, adopt for the temperature of the fusion of ice + 273°.0 with an uncertainty in this number of at least 0°.2.

CHAPTER II.

NORMAL THERMOMETER.

Sèvres Thermometer.—This thermometer is a constant-volume thermometer filled with pure, dry hydrogen, under the pressure of 1 meter of mercury at the temperature of melting ice. It consists of two essential parts: the *reservoir*, enclosing the invariable gaseous mass, and the *manometer*, serving to measure the pressure of this gaseous mass.

The *reservoir* is made of a platinum-iridium tube whose volume is 1.03899 liters at the temperature of melting ice. Its length is 1.10 m., and its outer diameter 0.036 m. It
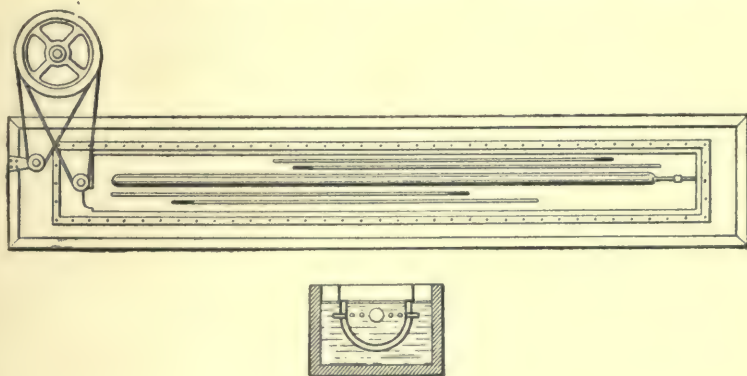
FIG. 1.

is attached to the manometer by a capillary tube of platinum of 0.7 mm. diameter. This is as small as is safe to make this tube on account of the otherwise too slow establishment of pressure equilibrium.

This reservoir is supported horizontally in a double box with interior water circulation. For the determination of the 100° mark indispensable for standardization, the reservoir can be placed in the same way in a horizontal heater supplied with steam and composed of several concentric coverings.

Manometer.—The manometric apparatus is mounted upon an iron support of 2.10 m. height, which is made of a railway rail firmly bolted to a tripod of wrought iron. The lateral parts attached to this rail, planed their entire length, carry sliding pieces to which are fastened the manometer tubes and a barometer. Fig. 2 represents, in a slightly modified form, the manometric apparatus. It is composed essentially of a manometer open to the air whose open arm serves as cistern for a barometer. The other arm, closed half-way up by a piece of steel, is attached to the thermometric reservoir by the capillary tube of platinum. The two manometer tubes, each of 25 mm. interior diameter, have their lower ends fixed into a block of steel. They communicate with each other by holes of 5 mm. diameter bored in the block. A stop-cock permits closing this connection. A second three-way cock is screwed on the same block. One of its branches can serve to let mercury run out; the other, to which is attached a long flexible steel tube, puts the manometer in communication with a large reservoir of mercury which can be raised or lowered the length of the support, either rapidly by hand, or slow-motioned by means of a screw.

The barometer which sets in the open branch is fixed at its upper part on a carriage whose vertical displacement is regulated throughout a length of 0.70 m. by a strong screw. The latter is held at its two ends by two nuts which permit it to turn without longitudinal motion; it works in a screw attached to the carriage, and carries at its

lower end a toothed pinion which works into a cog-wheel. It suffices to turn this wheel by acting upon the rod which serves as axis in order to raise or lower the carriage with
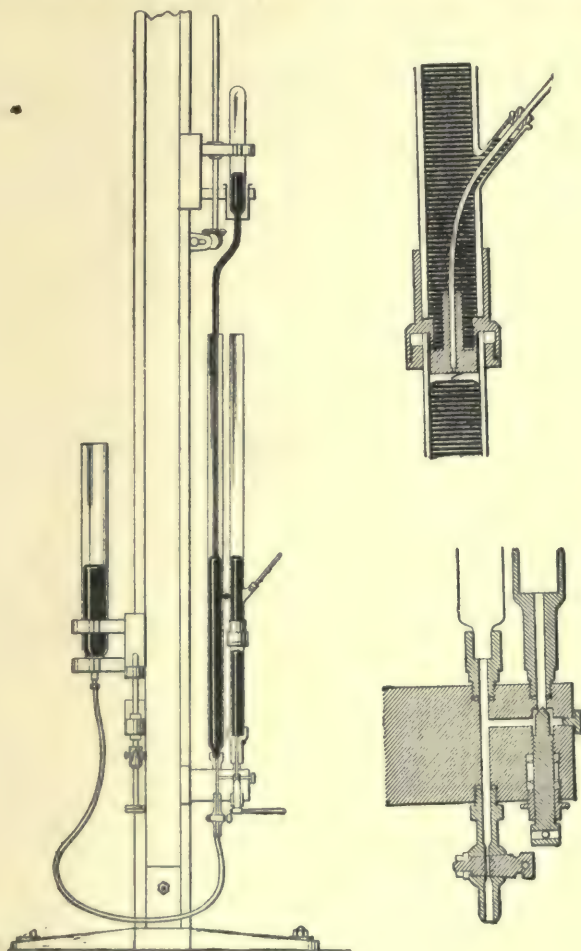
FIG. 2.

the barometer tube. This last has a diameter of 25 mm. in its upper part. The chamber is furnished with two indices of black glass soldered to the interior of the tube at 0.08 m. and 0.16 m. from the end. The points of these

indices, convex downwards, sensibly coincide with the axis of the barometric chamber. The part of the barometer which fits into the open manometer arm has a diameter greater than 0.01 m., and ends below in a narrower tube curved upwards.

The piece of steel which ends the closed arm is adjusted to this tube like a cock, leaving between itself and the tube but a very slight space, which is filled with sealing-wax. It rests upon the upper rim of this tube, to which it is besides pressed by leather washers tightly screwed up. At its lower end it terminates in a perfectly smooth polished plane, which is adjusted to be horizontal. In the middle of this surface, near to the opening of the canal which prolongs the joining tube, there is fixed a very fine platinum point, whose extremity, meant to be used as a reference-mark, is at a distance of about 0.6 mm. from the plane surface.

Above this piece is a tube of 25 mm. interior diameter, open above and connected below to the open arm of the manometer.

Since the measurement of a column of mercury is more easily made and with greater precision when the menisci whose difference of level it is desired to find are situated along the same vertical, the barometer is bent so as to bring into the same vertical line the axis of the closed arm of the manometer and that of the barometer. Under these conditions, the communication between the two manometer arms being established, the total pressure of the gas enclosed in the reservoir of the thermometer is given by the difference of level of the mercury in these superposed tubes.

The measurement of the pressures is made by means of a cathetometer furnished with three telescopes, each of which is provided with a micrometer and level. The micrometer circle is divided into 100 parts; at the distance

from which the manometer is read, each division of the circle corresponds to about 0.002 mm.

The method adopted for the measurement of pressures consists in determining the position of each mercury meniscus in terms of a fixed scale, hung near the manometer tubes, at the same distance as these latter from the telescopes of the cathetometer.

One of the principal difficulties arising in the measurement of pressures is that of the lighting of the menisci. The method employed by Chappuis consists in bringing up to the surface of the mercury an opaque point until its image reflected by the mercury appears in the observing telescope at a very small distance from that of the point itself. These two images being almost in contact, it is easy to set the micrometer cross-wire midway between them, at the precise point where would be the image of the reflecting surface. In order to have a very sharp image of the point, it is well to illuminate from behind by means of a beam of light passing through a vertical slit. The point and its image then stand out black on a bright background. The use of styles of black glass is preferable to that of steel points on account of their unchangeableness and of the greater sharpness of their edges.

The method with styles cannot be advantageously employed except in wide tubes, where the reflecting surface of the mercury which aids in the formation of the image does not have a sensible curvature.

Waste Space.—This consists of the space occupied by the gas: (1) in that part of the capillary tube which does not undergo the same variations of temperature as the thermometric reservoir; (2) in the piece of steel forming the plug which caps the closed arm of the manometer; (3) in the manometer tube between the mercury and the horizontal plane in which ends the piece of steel. The

mercury is supposed to just touch the style serving as reference-mark.

The capacity of the tube has been determined by mercury calibration; it was found equal to 0.567 cc. The length of the capillary tube being 1 m., if we deduct from this capacity that of 3 centimeters of the tube which are exposed to the same temperatures as the reservoir, that is 0.015 cc., this leaves 0.552 cc.

The capillary tube fits for a length of 27 mm. into the piece of steel serving as plug. The total thickness of this plug is 28.3 mm.; thus the portion of the canal included between the end of the capillary tube and the lower face of the plug is 1.3 mm. in length. As its diameter is 1.35 mm., the capacity of this canal is 0.0019 cc.

The space included between a cross-section of the manometer tube passing through the style and the plane surface of the plug is 0.3126 cc.

To have the total volume occupied by the gas it is necessary to add as well to this space the volume of the depressed mercury in the manometric tube caused by the curvature of the meniscus. The radius of this tube being equal to 12.235 mm., we find for this volume 0.205 cc.

We thus have as the total of the waste space the sum of the following volumes:

		cc.
Capacity of capillary tube	....	0.5520
Volume of canal in the plug	....	19
Capacity of the manometer tube between the style and the plane	....	3126
Volume of depressed mercury	....	2050
Total waste space	....	1.0715

When the mercury does not just touch the style, we shall have to add to this value, 0.4772 cc. per millimeter separation of the style from the top of the meniscus.

The *expansion of the metal of the bulb* has been measured by Fizeau's method; this volume has at different temperatures the following values:

	Liters.
20°	1.03846
0	1.03899
20	1.03926
40	1.04007
60	1.04061
80	1.04117
100	1.04173

The *variation of the capacity of the bulb* due to changes of pressure has also been studied; per millimeter of mercury it is 0.02337 $\overline{\text{mm.}}^3$; or

For 0 mm.	0 $\overline{\text{mm.}}^3$
" 100	2.3
" 200	4.7
" 300	7.0
" 400	9.3

The zero is verified from time to time by bringing the bulb to the temperature of melting ice; there is absolute constancy even after heating to 100°. The deviation is at the most 0.03 mm. for a pressure of 995 mm.

H. L. Callendar's Thermometer.—For the graduation of the platinum resistance-thermometer Callendar has studied an arrangement of the gas-thermometer in which the waste space is reduced to a minimum by an ingenious device which consists in interposing in the capillary tube a column of sulphuric acid which is always brought to the same position. It is then permissible to leave vacant spaces in the manometer of any volume, and this simplifies the measurements.

The *bulb* is of glass, and its capacity is 77.01 cc. The capillary tube has a diameter of 0.3 mm. It is attached to a small U tube of 2 mm. diameter which contains the

sulphuric acid.   The total value of the waste space is thus
reduced to 0.84 cc.

The sulphuric acid before each measurement is brought
up to a reference-mark.   The density of this liquid being
one-seventh that of mercury, the errors made in determin-
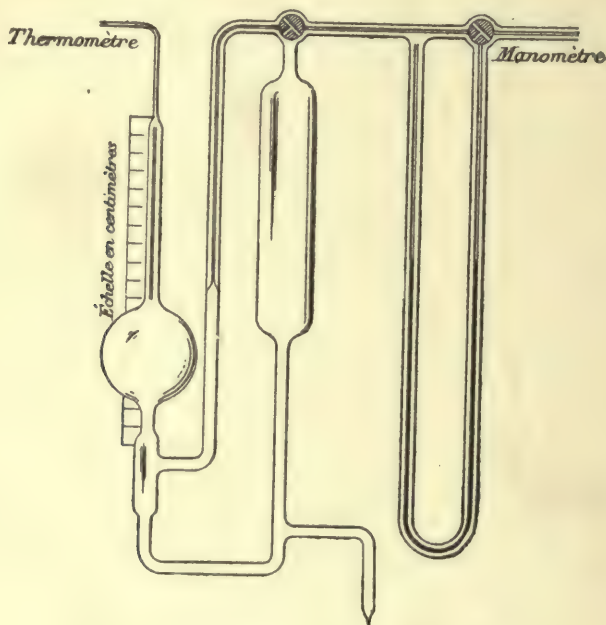
FIG. 3.

ing its level should be divided by seven to express them in
heights of mercury.   The use of this column of sulphuric
acid has the inconvenience to oblige the experimenter to
watch constantly the apparatus during the whole time of
heating and cooling in order to maintain the pressure
equilibrium in the two parts of this column; otherwise the
liquid would be driven into the manometer or absorbed
into the bulb.

The *manometer* is one open to the air and is read con-
jointly with the height of the barometer.

The *coefficient of expansion* of the hard glass used in the construction of the thermometer was measured for a tube of same make by means of two microscopes carried upon a micrometer-screw. A cold comparison-tube could be placed under the microscopes to verify the invariability of their distance apart.

MEAN COEFFICIENT OF EXPANSION.

t	a
17°............................0.00000685	
102	706
222	740
330	769
481	810

After heating to 400° there were permanent changes amounting to from 0.02 to 0.05 per 100.

If the zero is taken at intervals of time of varying length, permanent displacements are noted. The following table gives some examples:

Date.	Oxygen-thermometer.	Nitrogen-thermometer.	Remarks.
	mm.	mm.	
Jan. 21, 1886	693.1	695.4	{ Filled at 300°; measurement taken 4 days later
" 22, "	692.9	695.1	
" 23, "	692.9	694.9	After heating to 100°
" 25, "	692.0	693.8	
" 25, "	692.0	694.1	" " " "

This change of zero has been attributed to a partial absorption of the air by the glass. Glass, an amorphous body resembling liquids somewhat, dissolves gases, especially at high temperatures.

For temperatures higher than 300° this source of error becomes very serious, especially if the gas is hydrogen. This gas disappears progressively by solution in the glass or by oxidation replacing elements of the glass. It is

necessary to revert to nitrogen. This fact was observed by Chappuis and Harker in the course of a study of the platinum resistance-pyrometer when the temperatures measured reached as high as 600°.

Thermometer for High Temperatures. — Up to the present time there has not yet been realized for the measurement of high temperatures a gas-thermometer sufficiently precise to be considered a normal apparatus. We shall point out, in studying the gas-pyrometers, the conditions that such an apparatus should fulfil, and the reasons for these conditions. We shall in this place give only a brief summary.

The gas should be nitrogen.

The bulb should be of porcelain enamelled inside and out.

The measurements should be made by the method of the thermo-volumenometer or by any other method which does not entail an invariability of the gaseous mass throughout a very considerable period of time.

In its actual condition the normal Sèvres thermometer permits of measurements up to 100°.

That of Callendar has been employed up to 600°, and could without doubt with a porcelain bulb be used up to 1000°.

It would be possible to reach, by the method of the volumenometer, 1300°. To go higher it would be necessary to manufacture a special porcelain less fusible than the ordinary hard porcelain, or, this failing, return to platinum in an oxidizing atmosphere, by which means it might be possible to reach 1600°.

CHAPTER III.

GAS-PYROMETER.

THE gas-thermometer, as we have seen above, need not of necessity be used for the measurement of temperatures; it suffices to make use of it for the standardization of the different processes employed in the determination of temperatures, but *à priori* there are not on the other hand any absolute reasons for discarding it in cases other than these standardizations. Indeed it has often been employed. We shall examine the various trials that have been made with it, and discuss the results of them.

Substance of the Bulb.—The most important point to consider is the choice of the substance which constitutes the bulb; it is necessary to know its expansion to account for the variation of its volume under the action of heat; one must be sure of its impermeability.

Three substances have been used up to the present time to make these bulbs: platinum, iron, and porcelain.

Platinum, in spite of its high price, was employed by Pouillet and Becquerel; it has the advantage over iron in not being oxidizable, over porcelain in not being fragile. Its coefficient of expansion increases in a regular manner with the temperature:

	Between 0° and 100°.	Between 0° and 1000°.
Mean linear coefficient........	0.000007	0.000009

In the course of a lively discussion between H. Sainte-Claire-Deville and E. Becquerel the former of those savants discovered that platinum was very permeable to hydrogen, a gas whose presence is frequent in flames at points where

the combustion is not complete. Platinum was accordingly completely abandoned, perhaps wrongly; it is possible, in very many cases, to be sure of the absence of hydrogen, and the very precise experiments of Randall have shown that red-hot platinum was quite impermeable to all gases other than hydrogen, even with a vacuum inside the apparatus.

The only advantage of iron is its cheapness; it is as permeable to hydrogen as is platinum; it is not merely oxidizable in the air, but is besides attackable by carbonic acid and water-vapor. Thus the only gas that can be used with iron is pure nitrogen. The coefficient of expansion of iron is greater and increases more rapidly than that of platinum:

	Between 0° and 100°.	Between 0° and 100°.
Mean linear coefficient.........	0.000012	0.000015

Also this increase is not regular; there is produced at 850°, at the instant of the allotropic transformation, a sudden change of length, a contraction of 0.25 per cent.

It is very difficult to obtain pure iron; very small quantities of carbon modify somewhat the value of the coefficient of expansion. Besides, the change of state of steel at 710°, corresponding to recalescence, is accompanied in the heating by a linear contraction, varying with the amount of carbon present, from 0.05 to 0.15 per cent.

Porcelain was adopted as a result of the discussion between H. Sainte-Claire-Deville and Becquerel; it was considered as absolutely impermeable, but without decisive tests.

Even well-baked porcelain consists of a paste somewhat porous and permeable; it is only the glazing that assures its impermeability. But this covering may sometimes not be whole; as it softens above 1000°, it is susceptible of cracking if left for a considerable time with an excess of pressure on the interior of the apparatus. According to

Holborn and Wien, the glazing is broken after reaching 1100°, when a considerable difference of pressure is established in the direction of the lifting up of this glazing.

Finally like all verres, porcelain dissolves gases, and in particular water-vapor, which passes through it quite readily. A pyrometer left a long time in the flame at about 1200°, becomes filled with water-vapor which can be seen to condense in the manometer after a few weeks.

The experiments of Crafts have shown that the rapidity of the passage of water-vapor through porcelain, in a pyrometer of from 60 to 70 cc. capacity at the temperature of 1350°, was 0.002 grm. of water-vapor per hour.

It is thus not safe to employ porcelain at temperatures higher than 1000°, at least not in the thermometric processes which suppose the invariability of the gaseous mass.

The expansion of porcelain has been the object of a great number of measurements which, for porcelains of very different make, give values near to one another; the mean linear coefficient between 0° and 1000° varies between 0.0000045 and 0.000005 for hard porcelain—that is to say, baked for a long time at a temperature in the neighborhood of 1400°.

Here are the results of experiments made by Le Chatelier and by Coupeaux; the experiments were made with porcelain rods 100 mm. in length, and the numbers below express the elongation of these rods in millimeters:

Porcelain.	Temperatures.					
	0°	200°	400°	600°	800°	1000°
Bayeux..................	....	0.075	0.166	0.266	0.367	0.466
Sèvres dure (cuite à 1400°)...	....	.078	.170	.270	.378	.470
Limoges..................	....	.076	.168	.268	.360	.465
Sèvres nouvelle (cuite à 1400°)	....	.090	.188	.290	.390	.490

These numbers should be multiplied by three to give the cubical expansion.

Porcelain has still another inconvenience: the glazing is put on the outside only of vessels, so that the porosity of the paste gives an uncertainty due to the unequal absorption of gases at increasing temperatures.

According to Barus, it is impossible to fill with dry air a pyrometer, not glazed inside, at ordinary temperatures. The water is not driven out by pumping out several times and letting in dry air. An apparatus filled in this way will indicate between melting ice and boiling water from 150° to 200°. Nor is filling the apparatus at 100° satisfactory: it will indicate 115° for this same interval of 100°. Barus thinks that at 400°, by repeating the operation several times, one can consider the apparatus as filled with dry air.

Corrections and Causes of Error.—1. *Thermometer at Constant Volume.*—We must now render more precise the formula of the air-thermometer, by taking account of the variations of volume of the bulb, of the surrounding air-temperature which changes the density of the mercury, and finally of the volume of the waste space.

We have three series of observations to make in order to determine a given temperature:

$$P_0 V_0 = n_0 R T_0, \quad \cdots \cdots \quad (1)$$
$$P_{100} V_{100} = n_{100} R T_{100}, \quad \cdots \cdots \quad (2)$$
$$P V = n R T. \quad \cdots \cdots \quad (3)$$

Putting

$$T = \frac{1}{\alpha} + t;$$

the first two series serve to determine $\frac{1}{\alpha}$.

It is preferable, except in researches of very great pre-

cision, to take $\dfrac{1}{\alpha}$ from previously obtained results, and not to make the observations at 100°, unless one does so to check his experimental skill.

Dividing the third equation by the first, we have the relation

$$\frac{PV}{P_0V_0} = \frac{H\Delta_0 V}{H_0\Delta V_0} = \frac{nRT}{n_0RT_0} = \frac{nT}{n_0T_0}, \quad \cdot \quad \cdot \quad (4)$$

where H and H_0 are the heights of mercury, Δ and Δ_0 the densities of this metal.

For a first approximation let us neglect the differences between V and V_0, n and n_0, Δ and Δ_0. We shall have then an approximate value T' for the temperature sought:

$$T' = \frac{1}{\alpha} \cdot \frac{H}{H_0}, \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (5)$$

for

$$T_0 = \frac{1}{\alpha}.$$

Let us find now the *correction* dT to T' to obtain the exact temperature. In order to find this, take the logarithmic differential of (4):

$$\frac{dT}{T'} = \frac{d\Delta}{\Delta_0} + \frac{dV}{V_0} - \frac{dn}{n_0}. \quad \cdot \quad \cdot \quad \cdot \quad (6)$$

Then determine the values of the different terms; let t_1 and t_2 be the absolute temperatures of the surroundings when the bulb is at the temperatures T' and T_0.

1.
$$\frac{d\Delta}{\Delta_0} = \frac{\Delta - \Delta_0}{\Delta_0},$$
$$\Delta = \Delta_0 \cdot [1 - k(t_2 - t_1)],$$
$$k = 0.00018(t_2 - t_1),$$

$$\frac{d\varDelta}{\varDelta_0} = -\,0.00018(t_2 - t_1).$$

2.
$$\frac{dV}{V_0} = \frac{V - V_0}{V_0},$$

$$V = V_0[1 + k'(T' - T_0)],$$

$$k'(\text{porcelain}) = 0.0000135,$$

$$\frac{dV}{V_0} = 0.0000135(T' - T_0),$$

by neglecting the variations of volume of the bulb due to changes of pressure.

3.
$$-\frac{dn}{n_0} = \frac{x_2 - x_1}{n_0},$$

in calling x_2 and x_1 the number of molecules contained in the waste space ϵ at the temperatures t_2 and t_1. We have in fact, N being the total mass contained in the apparatus,

$$n = N - x_2,$$

$$n_0 = N - x_1,$$

$$n - n_0 = -\,(x_2 - x_1).$$

To determine x_1 and x_2:

$$P_0\epsilon = x_1 R t_1,$$

$$P\epsilon = x_2 R t_2,$$

$$-\frac{dn}{n_0} = \frac{\epsilon}{V_0}\left(\frac{P}{t_2} - \frac{P_0}{t_1}\right) \cdot \frac{T_0}{P_0}.$$

In noting that

$$\frac{P}{P_0} = \frac{T'}{T_0},$$

we have

$$-\frac{dn}{n_0} = \frac{\epsilon}{V_0}\left(\frac{T'}{t_2} - \frac{T_0}{t_1}\right).$$

Put

$$t = \frac{t_1 + t_2}{2},$$

$$\theta = \frac{t_1 - t_2}{2}.$$

After substitution we have

$$\frac{dn}{n_0} = - \frac{\epsilon}{V_0} \cdot \left(\frac{T' - T_0}{t} - \frac{\theta}{t} \cdot \frac{T' + T_0}{t} \right).$$

These successive transformations are for the purpose of making evident from the formula:

1. The ratio between the waste space and the total volume: $\frac{\epsilon}{v_0}$;

2. The temperature measured: $T' - T_0$;

3. The variation of the surrounding temperature θ;

which are the three essential factors on which depends the correction in question.

Formula (6) then becomes:

$$\frac{dT}{T'} = - 0.00018(t_2 - t_1) + 0.0000135(T' - T_0)$$

$$- \frac{\epsilon}{V_0} \cdot \left(\frac{T' - T_0}{t} - \frac{\theta}{t} \cdot \frac{T' - T_0}{t} \right).$$

Let us take a numerical example in order to show the importance of these correction terms in the three following cases:

$$T' - T_0 = 500°,$$
$$T' - T_0 = 1000°,$$
$$T' - T_0 = 1500°.$$

In taking

$$\frac{\epsilon}{V_0} = 0.01,$$
$$t = 27° + 273° = 300°,$$
$$2\theta = 10°,$$

we have

$$dT_{500} = -\ 1°.4 +\ 5°.15 + 13°.1 =\ 16°.85,$$
$$dT_{1000} = -\ 2°.3 + 17°.0\ + 38°.2 =\ 52°.9,$$
$$dT_{1500} = - 30°.7 + 35°.7\ + 90°.0 = 122°.5.$$

These figures show the very great importance of the waste space, whose exact volume it is impossible to know. This method of computation of the corrections by logarithmic differentials is only approximate, and is not sufficient for real measurements, but it renders more clear the general discussion of the causes of error.

Let us see what uncertainty in the temperature may result from the uncertainty which there may be in the volume of the waste space. In reality there is a continuous passage from the high temperature of the pyrometer to the surrounding temperature on a length which may vary from 10 to 30 centimeters, according to the thickness of the walls of the furnace. The volumes of the bulb and of the waste space which should be taken in order that the above formulas be exact should be such that the real pressure is equal to the pressure that would exist in supposing that a complete and sudden change of temperature took place at a definite fictitious point, separating the heated part from the cold part of the apparatus. The probable position of this point is estimated, and if the estimation is poorly made, two errors are committed, one on the real volume heated and the other on the waste space, errors equal and of opposite sign so far as the volume is concerned.

To calculate this *error*, as in the case of the corrections, we may employ the method of logarithmic differentials.

Applying the same formula as before, we find for the relative error $\dfrac{dT}{T}$:

$$\frac{dT}{T} = -\frac{dV}{V_0}\left(\frac{T' - T_0}{t} - \frac{\theta}{t} \cdot \frac{T' + T_0}{t}\right);$$

and neglecting the second term of the parenthesis, which is relatively very small,

$$\frac{dT}{T} = -\frac{dV}{V_0}\left(\frac{T' - T_0}{t}\right).$$

Letting the section of the capillary tube be equal to 1 sq. mm., the volume of the bulb 100 cc., and assuming an uncertainty of 100 mm. in the position of the transition-point, a value often not exaggerated, we find the following errors in the temperatures:

$$dT_{500} = 1°.7,$$
$$dT_{1000} = 3°.9,$$
$$dT_{1500} = 8°.5.$$

We thus see that at 1000° the error resulting from the uncertainty in the origin of the waste space may reach several degrees for a bulb of 100 cc.

A second cause of error results from the changes of mass following the ingoings and outgoings of gas. As before, we have

$$\frac{dT}{T} = -\frac{dn}{n_0}.$$

Consider the experiments of Crafts. There enters per hour at 1350° in a bulb of porcelain of 100 cc., 0.002 grm. of water-vapor, or 0.225 milligramme-molecules; the

initial volume enclosed at the start is 4.5 milligramme-molecules:

$$\frac{dT}{T} = \frac{0.225}{4.5} = 0.05,$$

which leads to an error of

$$dT_{1350°} = 70° \text{ (about)}$$

for an experiment lasting one hour.

This computation demonstrates clearly the enormous errors which may result from the penetration of an outside gas during the time of one hour, a length of time much less than that of an ordinary experiment. It is true that this error decreases rapidly with rise of temperature, and it is very probably zero at 1000°, if there is no break in the glazing.

2. *Constant-pressure Thermometer.* — We still employ the same formula (4):

$$\frac{H \Delta V}{H_0 \Delta_0 V_0} = \frac{nRT}{n_0 R_0 T_0},$$

which gives for a first approximation

$$\frac{T'}{T_0} = \frac{n_0}{n}.$$

Calling t_1 and t_2 the surrounding absolute temperatures corresponding to T_0 and T_1, u_1 and u_2 the corresponding volumes of the waste space and of the reservoir, we have, for the determination of n and n_0, the relations:

$$n_0 = N - x_1 = \frac{H_0 \Delta_0 V_0}{t_2 \cdot t_1},$$

$$n = N - x_2 = n_0 - (x_2 - x_1),$$

$$x_2 = \frac{H \Delta u_2}{R t_2},$$

$$x_1 = \frac{H_0 \Delta_0 u_1}{R t_1}.$$

As before, there is a correction to be applied to the approximate temperature T' thus obtained:

$$\frac{dT}{T'} = \frac{dH}{H_0} + \frac{d\Delta}{\Delta_0} + \frac{dV}{V_0},$$

an expression the values of whose terms are known.

Let us see now the causes of error and discuss their importance.

The error resulting from the uncertainty in the boundary of the hot and cold volumes is

$$\frac{dT}{T'} = \frac{dn_0}{n_0} - \frac{dn}{n} = \frac{dn}{n_0}\left(1 - \frac{T'}{T_0}\right) = -\frac{dn_0}{n_0}\left(\frac{T' - T_0}{T_0}\right).$$

As before, let

$$\frac{dn}{n_0} = \frac{1}{1000}.$$

Then we find

$$dT_{500} = 1°.5,$$
$$dT_{1000} = 5°.0,$$
$$dT_{1500} = 9°.3.$$

Thus the errors due to this cause are still greater than by the method of constant volume.

In order to make exactly the correction for the waste space, the method of Regnault's *compensator* may be employed, as in the work of Sainte-Claire-Deville and Troost; this allows of placing the measuring apparatus at a considerable distance from the fire, which makes the experiments much easier.

Let us now examine the error resulting from the entrance of exterior gases:

$$\frac{dT}{T'} = \frac{dn}{n} = \frac{dn_0}{n_0} \cdot \frac{T}{T_0}.$$

For the experiment of Crafts, the error would be 413° instead of 70°, the bulb being filled at the start at atmospheric pressure.

It is thus evident that, from all points of view, the method of constant volume is more precise than that of constant pressure; the lack of impermeability of the coverings is the only hindrance preventing the use of the former in practice.

3. *Volumenometric Thermometer.*—The only rational method for the measurement of high temperatures is, as we have already said, that of the volumenometer of Becquerel, which does not require the invariability of the gaseous mass throughout the duration of the experiment. It consists in measuring the changes of pressure resulting from a given variation of the gaseous mass contained in the bulb. Becquerel employed very slight changes of mass; the changes of pressure are then equally slight, which diminishes the precision of the measurements.

There is no theoretical inconvenience in reaching an absolute vacuum, or, what is practically more simple, using the exhaustion given by a water-pump, as was done by Mallard and Le Chatelier; this considerably increases the precision. If the exhaustion is complete, we have the relation

$$\frac{PV}{RT'} = n = \frac{P_0 u_0}{RT_0},$$

u_0 being the volume of the reservoir corresponding to the surrounding temperature T_0. If the two volumes are filled under atmospheric pressure, $P = P_0$, and then

$$\frac{T'}{T_0} = \frac{u}{V}.$$

There are two corrections to make: the first relative to the expansion of the envelope, the second to the difference

between P and P_0 when the exhaustion is produced by a water-pump:

$$\frac{dT}{T'} = \frac{dP}{P} + \frac{dV}{V}.$$

In general dP is in the neighborhood of 15 mm. of mercury, which gives

$$\frac{dP}{P} = 0.02.$$

Also,

$$\frac{dV}{V} = 0.0000135(T' - T_0),$$

$$\frac{dT}{T'} = -0.02 + 0.0000135(T' - T_0).$$

Calculating this correction for different temperatures, we have

$$dT_{500} = -10°.4,$$
$$dT_{1000} = -8.5,$$
$$dT_{1500} = -0.35.$$

Let us compute now the error which comes from the uncertainty in the position of the line of separation of the warm part and the cold part of the apparatus; it is, besides, the only remaining one:

$$\frac{dT}{T'} = \frac{dV}{V}.$$

As before, assuming the higher limit to be $\frac{1}{1000}$,

$$\frac{dT}{T'} = \frac{1}{1000},$$

which leads to

$$dT_{500} = 0°.77,$$
$$dT_{1000} = 1.27,$$
$$dT_{1500} = 2.77.$$

From every point of view, this method is thus preferable to the others.

This whole discussion of the sources of error in the measurement of temperatures aims merely to obtain a determination of the temperature of the pyrometer employed. But this temperature is in itself not the real object of the measurements; it is but an intermediary to arrive at a knowledge of the temperature of certain other bodies supposed to be in thermal equilibrium with the pyrometer. Now this equilibrium is extremely difficult to realize, and it is more often the case that there is no way of being sure of the exactitude with which it has been obtained. Here is then a new source of error very important in the measurement of temperatures, especially of high temperatures, at which radiation becomes an important consideration. Within an enclosure whose temperature is not uniform, which is true for the majority of furnaces, there may exist enormous differences of temperatures between neighboring parts. One cannot too strongly insist upon the presence of this source of error, with whose existence too many investigators have not sufficiently occupied themselves.

Experimental Results.—We shall study now the experiments made by various savants, and we shall see in what degree the conditions of precision indicated in the course of this account have been realized.

Experiments of Pouillet.—Pouillet was the first to make use of the air-thermometer for the measurement of high temperatures; he obtained very good values for the epoch at which he worked.

His pyrometer was made of a platinum bulb, of ovoid form, of 60 cc. capacity, to which was gold-soldered a platinum capillary tube of 25 cm. in length; continuous with this tube was another of silver of the same

length, fastened to the manometer. The joining of the platinum and silver tubes was made by means of a metal

FIG. 4.

collar (Fig. 4). The waste space had thus a volume of 2 cc.

The manometer was made up of three glass tubes embedded at their lower ends in a metallic piece: the first tube serving as measurer was graduated in cubic centimeters, the second constituted the manometer properly speaking, and the third served to fill the apparatus.

A cock conveniently placed permitted variation of the quantity of mercury contained in the apparatus (Fig. 5). The principle of this apparatus is the same as that of the more recent Regnault manometer; this latter differs from the manometer of Pouillet only in the suppression of the third tube, which is replaced by a bottle joined to the emptying-cock by a rubber tube.
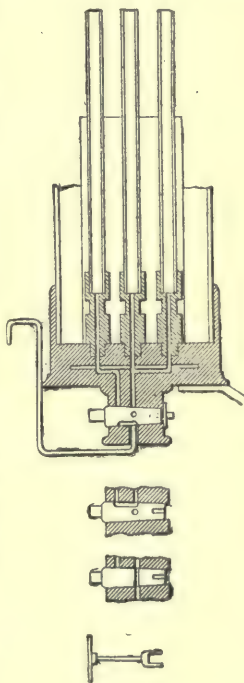
Errors: 1. According to Pouillet, it was impossible to carry the measurements up to 120°; there was complete

FIG. 5.

disaccordance with the readings of the mercury-thermometer; he attributes this non-agreement to the condensa-

tion of air on the platinum. Becquerel showed later that this was due to the presence of water-vapor in the insufficiently dried air.

2. Not being able to use the 100° mark for the determination of the coefficient of expansion of air, Pouillet took the number 0.00375, given by Gay-Lussac, instead of the correct number, 0.00367. This is the principal source of error in his measurements. The following table permits a comparison of his results for the specific heats of platinum with those obtained by Violle:

	100°	300°	500°	700°	1000°	1200°
Pouillet, $\alpha = 0.00375$. ...	0.0335	0.0343	0.0352	0.0360	0.0373	0.0380
" $\alpha = 0.00367$.....	328	336	345	353	366	373
Violle...................	323	535	347	359	377	389

Fusing-points.—Pouillet's determinations of fusing-points are far less good:

> Gold...................... 1180° (too high by 110°)
> Silver..................... 1000 ("   "   "   40°)
> Antimony................. 432 (too low by 200°)
> Zinc...................... 423 (good)

The possible sources of error are the following:

1. Introduction of hydrogen into the platinum bulb, which should raise too high the temperature-measurement and diminish the specific heat of platinum; the fusing-points of gold and silver are too high.

2. Equilibrium of doubtful temperature with the furnace as arranged. A glass tube, heated from below by coal, would necessarily be more strongly heated near the base; it would then have been necessary, in order to have accurate measurements by this arrangement, certainly very irregular as to temperature, that the substance and the thermometer be in the same conditions with respect to radiation (Fig. 6).

For antimony the error is certainly due to some particular cause; or perhaps the very impure metal was mixed with lead, or there may have been a mistake in computation. Nevertheless the number 432 was the only one used up to the recent memoir of Gautier on the fusibility of alloys.

Experiments of Ed. Becquerel. —This savant took up and continued the work of Pouillet with the same apparatus. But at the close of a discussion with H. Sainte-Claire-Deville on the ques- tion of the permeability of plati-

FIG. 6.

num, he made use successively of pyrometers of iron and of porcelain. The results obtained with platinum seem, however, to be far the best.
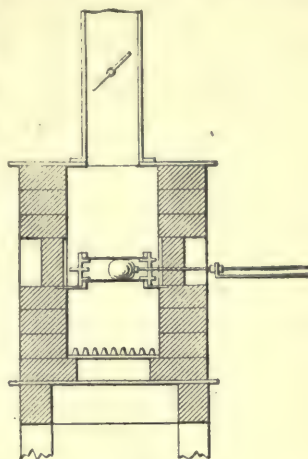
	Pyr. of Pt.	Pyr. of Porcelain.
Boiling-point of zinc................	930° (good)	890°
Fusing-point of silver	960 "	916
Fusing-point of gold................	1092	1037

The figures for gold differ among themselves by about 25°, more or less.

It is difficult to explain these differences, which are probably due to inequality of temperature between the pyrometer and the metal under investigation, resulting perhaps from a difference in their emissive powers.

Experiments of H. Sainte-Claire-Deville and Troost.— They, after their discussion with Becquerel, made numer- ous experiments with the porcelain air-thermometer; they obtained very discordant results, which they did not publish at the time.

They placed the most confidence in the determinations

made by the aid of the vapor of iodine (we shall speak of this later); but when the inaccuracy of this method was pointed out, they made known the results that they had obtained for the boiling-point of zinc.

They employed a crucible of plumbago having a capacity of 15 grms. of zinc; the metal was added anew as fast as it evaporated.

The crucible was placed in a furnace filled with coal. Around the pyrometer was arranged a covering of fire-clay; but this arrangement was quite insufficient to eliminate errors due to radiation. The same measurements were repeated with different gases.

Figures obtained:

Gas.	First Series.	Second Series.	Third Series.
Air...........	From 945° to 955°	From 940° to 948°	From 928° to 932°
Hydrogen ...	" 925 to 924	" 916 to 924	
Carbonic acid.	1067	1079	

The deviations seem to be a function of the nature of the gas, which is inexplicable; it would be necessary to admit of an enormous dissociation of the carbonic acid in order to explain the temperatures found with this gas.

Later this method was modified. The gas enclosed in the pyrometer was removed by means of the mercury-pump, either warm or after cooling. But this method did not possess any real advantages; the entrance of the gas and vapors during the reheating is not avoided; besides, during the cooling, there is danger of the entrance of air by leaking of the cock placed at the outlet of the pyrometer. Troost found in this way 665° for the boiling-point of selenium; this figure is too high. As in the case of the determination of the boiling-point of zinc, the arrangement

for heating did not protect sufficiently against the radiation from the outer surfaces.

Violle's Experiment. — Guided by H. Sainte-Claire-Deville, whom his successive failures had instructed in the difficulties of the problem, Violle has made a series of measurements which are among the best up to the present time. He made use of a porcelain thermometer, and he worked simultaneously at constant pressure and constant volume. The agreement of the two numbers shows if the mass has remained constant; this is the equivalent of the method of Becquerel.

The most serious objection that can be made to these observations is as to the uncertainy of the equality of temperatures of the pyrometer and of the substance studied placed beside the former; from this point of view, however, these experiments, made in the Perrot furnace, were much more satisfactory than those made in coal-furnaces previously employed.

1. A first series of determinations was of the specific heat of platinum. A platinum mass of 423 grms. was put into a Perrot muffle alongside the pyrometer, and when the mass was in a state of temperature-equilibrium it was immersed, either directly in water or in a platinum eprouvette placed, opening upward, in the midst of the calorimeter-water. In the first case the experiment was made in a few seconds; in the second it lasted fifteen minutes, and the correction was as high as 0°.3 per 10°; the results, however, were concordant. At 787° two experiments gave 0.0364 and 0.0366; mean, 0.0365.

At 1000° twelve experiments were made employing the method of immersion; the numbers found vary from 0.0375 to 0.0379; mean, 0.0377.

Near 1200° the measurements were made at constant pressure and at constant volume.

Temperature at Constant Volume.	Temperature at Constant Pressure.	Mean.	Specific Heat of Platinum.
1171°	1165°	1168°	0.0388
1169	1166	1168	.0388
1195	1192	1193	.0389

The mean specific heat may be represented by the formula

$$C_0^t = 0.0317 + 0.000006 \, . \, t.$$

The true specific heat is equal to

$$\frac{dq}{dt} = 0.0317 + 0.000012 \, . \, t.$$

Violle used these determinations to fix, by extrapolation, the fusing-point of platinum, which he found equal to 1779°. He measured for that the quantity of heat given out by 1 grm. of solid platinum from its fusing-point to 0°. For this purpose a certain quantity of platinum is melted, into which is plunged a spiral wire of the same metal, and, at the instant that the surface of the bath solidifies, by aid of this wire a cake of solid platinum is lifted out and immersed in the water-calorimeter. Repeating the determination of this fusing-point, Holborn and Wien have found more recently 1780°.

The latent heat of fusion of platinum is equal to 74.73 c. ± 1.5; this number results from five determinations.

2. A second series of experiments was on the specific heat of *palladium;* the determinations were made, in part by comparison with platinum, in part by the air-thermometer. The results obtained by the two methods are concordant.

The mean specific heat is given by the formula

$$C_0^t = 0.0582 + 0.000010 \, . \, t.$$

The true specific heat is equal to

$$\frac{dq}{dt} = 0.0582 + 0.000020 \cdot t.$$

The fusing-point was found equal to 1500°; the more recent experiments of Holborn and Wien give 1580°. This difference can be explained by impurities in the metal and absorption of furnaces-gases.

The latent heat of fusion of palladium, measured by the same experiments, was found to be 36.3 calories.

3. In another series of experiments Violle has determined the boiling-point of zinc. He employed an apparatus of enamelled casting, heated in a triple envelope of metallic vapor; the top was covered with clay and cow-hair to prevent superheating of the coverings. The measurements were made with pressure and volume simultaneously variable.

Volume of bulk.... 294.5 cc.   Volume of gas let out 184.3 cc.
Waste space........ 4.7 "   Pressure 892.3 mm. $T = 929°.6$
t_0................. 3°.8 t_0 .... 7°.7
H_0............... 760.5 mm. H_0............... 759.5 mm.

Barus, Holborn and Wien found numbers very close to 930°.

4. A last series is relative to the fusing-points of metals, which were determined by comparison with the total heat of platinum:

Silver........................... 954° (too small by 10°)
Gold............................. 1045 ("   "   " 20)
Copper .... 1050 ("   "   " 20)

Experiments of Mallard and Le Chatelier.—In their investigations on the temperatures of ignition of gaseous mixtures, Mallard and Le Chatelier made use of a porcelain pyrometer, which was exhausted; then air was let in and the gaseous volume thus absorbed was measured. It is possible

to reach 1200° without noticing any breaking down of the porcelain; but this giving way is complete at 1300° under the action of the vacuum.

This method was used in the following way to measure the temperatures of ignition of gaseous mixtures. The air was exhausted from the apparatus, and the temperature was measured by the air-volume which filled it; the air was again exhausted and the apparatus was filled with the gaseous mixture. Whether or not there was ignition was known by the comparison of the volume of the mixture with that of the air introduced under the same conditions of temperature, at least in the cases of mixtures burning with contraction.

The pyrometer used had a capacity of 62 cc., after deduction of the waste space (1 cc.); the following table gives the volumes of air corresponding to different temperatures:

400°	26.7 cc.
600	20.6
800	16.7
1000	14.1
1200	12.2

In admitting that the measurements of volume be made to 0.1 cc., one should have a precision of only 10° in 1000° on account of the insufficient volume of the thermometric reservoir.

Experiments of Barus.—This American savant devised a rotating apparatus, remarkable for its uniformity of temperature, but he applied it directly only to the standardization of thermoelectric couples. He worked at constant pressure. By means of couples graduated in this way, he has determined the boiling-points of zinc (926°–931°) and of cadmium (773°–784°); the boiling-point of bismuth was found equal to 1200° under a reduced pressure of 150 mm., which would give under atmospheric pressure by extrapolation 1500°.

Fig. 7 represents the longitudinal section of Barus'
apparatus. It is composed essentially of a porcelain
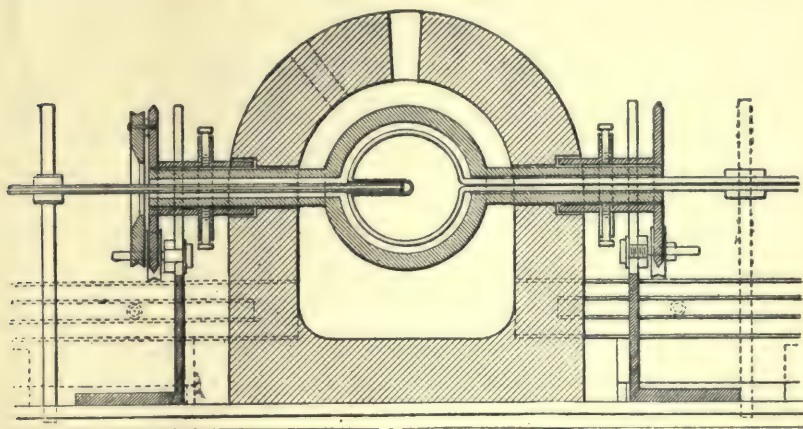
FIG. 7.

pyrometer containing an interior tube in which is placed
the couple. The pyrometer fixed at a point of its stem is
held immobile. It is surrounded by a muffle of casting
whose general shape is that of revolution about the axis of
the pyrometer; this muffle is composed of two similar
halves held by means of iron collars, and can be given a
motion of rotation about its axis of figure, in such a
manner as to assure uniformity of heating. It is heated
by gas-burners placed below. An outer covering of fire-
clay keeps in the heat about the iron muffle.

Experiments of Holborn and Wien.—Holborn and Wien
have made a very complete standardization of the thermo-
electric couple Pt—Pt-Rh proposed by Le Chatelier.
They made use of a porcelain reservoir of about 100 cc.
capacity, terminating at its two ends in capillary porcelain
tubes. The thermoelectric junction is placed inside the
bulb, and each of its wires is led out by one of the lateral
tubes; this arrangement allows of determining at various

points the real temperature of the waste space whose volume is 1.5 cc.

They worked at constant volume, with a very low initial pressure so as always to have depression; they were able to reach 1430°. Above 1200° they could make but a single observation with one pyrometer; below this, about ten observations.

They determined the coefficient of expansion of their porcelain, a product of the Berlin works, and found it equal to 0.0000045, the identical number given by Le Chatelier for the Bayeux porcelain.

They made use of this pyrometer, employing as intermediary a couple, to fix the fusing-points of certain metals:

Silver............................	970°
Gold..............................	1072
Palladium........................	1580
Platinum.........................	1780

These figures are to be counted among those which seem to merit the most confidence; however, it is necessary to note that the volume of the bulb was too small to assure a very great accuracy.

We shall return to these experiments when treating of electric pyrometers.

Arrangement of Experiments.—The discussion that we have just held permits us to define certain conditions to which should conform new experiments necessary to further the accuracy of fusing and boiling temperatures used as fixed points for the standardization of other pyrometers.

The bulb of the thermometer should be of porcelain enamelled inside and out, as were the bulbs made at Sèvres for certain experiments of Regnault and of H. Sainte-Claire-Deville.

The capacity of the bulb should be as nearly as may be

as great as 500 cc., the condition necessary in order that the error resulting from the waste space be certainly less than 1°.

The thermometric gas will be nitrogen.

The volumenometer method will be employed, or any equivalent method which does not suppose the invariability of the gaseous mass, and the greatest changes of pressure compatible with the resistance of the porcelain will be produced. Up to 1200° a high vacuum should be employed, since there is no danger of deforming the bulb.

Finally, most careful precautions will be taken to assure the equilibrium of temperature between the reservoir of the pyrometer and the body whose temperature it is desired to measure. Barus' arrangement seems to be theoretically entirely satisfactory, but it is quite complicated and costly. One can still make use of muffles completely surrounded with flames, as in the fabrication of porcelain; the temperature there is very uniform. But their use offers a serious practical difficulty; the stem of the pyrometer, although well protected, frequently breaks at the point where it passes through the compartment of flames.

It will be more practical, perhaps, to make use of liquid baths—non-volatile fused salts for example, kept in continuous agitation, in which plunge at the same time the thermometer bulb and the body whose temperature is to be found, the heating being obtained by the combustion of gas in a Perrot furnace, or by an electric current passing through a coil immersed in the bath.

If one has to use an ordinary gas-furnace, Perrot furnace, or, better, a Leger furnace, it will be necessary to explore by means of a thermoelectric couple the distribution of temperature in the whole region utilized.

<center>INDIRECT PROCESSES.</center>

We will place in this list various experiments in which the laws of the expansion of gases have been used only in an indirect way, or have been extended to vapors.

Method of Crafts and Meier.—It is a variation of the method of H. Sainte-Claire-Deville and Troost, consisting in removing the gas by means of. a vacuum. Crafts and Meier displaced the gas of the pyrometer by carbonic acid or hydrochloric acid, gases easily absorbable by suitable reagents. Hydrochloric acid is the more convenient, for its absorption by water is immediate; but there is to be feared at high temperatures its action on the air with formation of chlorine; it is preferable to employ nitrogen in place of air.

The apparatus (Fig. 8) consists of a porcelain bulb, whose inlet is large enough to let pass the entrance-tube of the gas, which reaches to the bottom of the bulb. This arrangement increases considerably the influence of the waste space, and consequently diminishes the precision of the determinations.
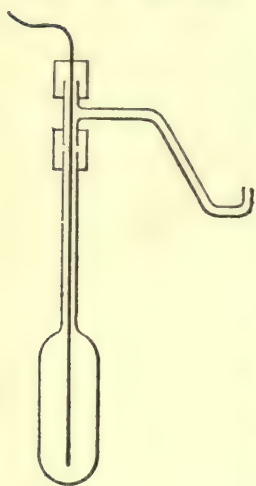
This method is especially convenient for observations on the densities of vapors which are made by the same apparatus; it then allows of having an approximate idea of the temperatures at which the experiments are made.

Fig. 8.

Crafts and Meier have in this way determined the variations in density of iodine vapor as a function of the temperature.

Regnault had previously proposed a similar method, without, however, making use of it.

1. One fills with hydrogen an iron vessel brought to the temperature that one desires to measure, and the hydrogen is driven out by a current of air; at the outlet of the metallic reservoir the hydrogen passes over a length of red-hot copper, and the water formed is absorbed in tubes of sulphuric acid in pumice-stone and weighed. This method, very complicated, is bad on account of the permeability of the iron at high temperatures.

At the same time, he proposed the following method:

2. An iron bottle containing mercury is taken; the vessel, being incompletely closed, is heated to the desired temperature and then allowed to cool, and the remaining mercury is weighed. This method is also defective on account of the permeability of iron at high temperatures; the hydrogen of the furnace-gases can penetrate to the inside of the recipient and drive out an equivalent quantity of mercury-vapor.

Methods of H. Sainte-Claire-Deville.—1. This savant tried in the first place to measure temperature by a process analogous to that of Dumas' determination of vapor-densities. He took a porcelain bulb full of air, and heated it in the enclosure whose temperature was wanted, and sealed it off by the oxyhydrogen flame with the autogène solder. He measured the air remaining by opening the bulb under water and weighing the water that entered, or else he determined merely the loss in weight of the bulb before and after heating.

Observations taken on the boiling-point of cadmium gave 860°. The data for the computation were as follows:

$$H = 766.4 \text{ mm.}$$

Volume of bulb   = 285 cc.
Volume of remaining air = 72 cc.

The computation may be made also in this way: Let 17° be the surrounding temperature; $T_e = 273° + 17° = 290°$.

$$T' = 290 \times \frac{285}{72} = 1150°.$$

The correction due to the expansion of the porcelain is

$$0.0000135 \times 850 = 13°,$$

which gives for the temperature of boiling cadmium

$$t = 1150° - 273° - 13° = 864°.*$$

The figure 860° is too high. There are in these experiments two possible sources of error: non-uniform heating on account of radiation, and the possibility of the existence of water-vapor in the bulb.

Besides, the small weight of the air and the difficulty of closing the recipient absolutely tightly render the experiments very delicate.

2. In a second method, which has the advantage of replacing the air by a very heavy vapor, Deville returned to the idea of Regnault, consisting in utilizing the vapor of mercury; but he ran against a practical difficulty. He had replaced the permeable iron recipients by porcelain recipients; the mercury condensed in the neck of the pyrometer and fell back in cold drops which caused the bulb to break.

For this reason he abandoned mercury and replaced it with iodine; the return of a cold liquid was completely obviated by reason of the nearness of the boiling-point of

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* This result differs slightly from that given by Sainte-Claire-Deville, because we have taken as coefficient of expansion of porcelain the most recently obtained value; besides, the assumed temperature of the surroundings, 17°, differs perhaps from the real one, which is not given.

this substance (175°) and its fusing-point (113°). A large number of observations were made by this method; the boiling-point of zinc, for example, was found to be equal to 1039°.

The data were:

$$H = 758.22 \text{ mm.}$$

Volume of bulb.......... ..... $= 277$ cc.
Increase in weight. Iodine $-$ air $= 0.299$ grm.
Volume of remaining air........ $= 2.16$ cc.
Density of iodine-vapor......... $= 8.716$

The computation can be made in the following way:

If the temperature of the surroundings is 17°, the theoretical weight of the iodine-vapor contained in the bulb at this temperature would be

$$1.293 \times 8.716 \times 0.277 \times \frac{273}{290} = 2.92 \text{ grm.}$$

The weight of iodine remaining in the reservoir is, taking note of the correction to be made resulting from the 2.16 grm. air which occupy 8.9 cc. at 930°,

$$0.299 + 1.293(0.277 - 0.00216)\frac{273}{290} = 0.634 \text{ grm.}$$

If there had been no air, the weight would have been

$$0.634 \times \frac{277 + 8.9}{277} = 0.652 \text{ grm.}$$

$$\frac{T'}{T_0} = \frac{2.920}{0.652},$$

$$T' = 1290°.$$

Making the correction for the expansion of porcelain (15°), we have

$$T' = 1290 - 273 - 15 = 1002°.$$

The difference between the result of this computation and that of Deville comes from similar reasons to those noted above (page 64, note 1).

This method is quite faulty, as the iodine does not obey the laws of Mariotte and Gay-Lussac. The vapor density of this substance decreases with rise of temperature, this effect being attributed to a doubling of the iodine molecule. This fact was established by Crafts and Meier and confirmed by Troost.

Temperatures.	445°	850°	1030°	1275°	1390°
Densities	8.75	8.08	7	5.76	5.30
$\dfrac{D_t}{D_{445}}$	1	0.92	0.80	0.66	0 66

Troost found 5.70 at the temperature of 1240°.

If, in the preceding computation, we take 7.8 as the density of iodine at the boiling-point of zinc, we then find a temperature lower than 150°, which is far too low.

Method of Daniel Berthelot.—All the preceding methods are limited by the impossibility of realizing solid envelopes resisting temperatures higher than 1500°. D. Berthelot has devised a method which, at least in theory, may be applied to any temperatures, however high, because there is no envelope for the gas, or at least no envelope at the same temperature. It is based on the variation of the index of refraction of gaseous mass heated at constant pressure; the velocity of light depends upon the chemical nature and the density of this medium, but is independent of its physical state. A gas, a liquid, or a solid of the same chemical nature produces a retardation of the light dependent only upon the quantity of matter traversed; this law, sensibly true for any bodies whatever, should be rigorously exact for substances approaching the condition of perfect gases. This retardation is measured by the displacement of interference fringes between two beams of

parallel light, the one passing through the cold gas, the other through the hot gas. In reality Berthelot employs a null method; he annuls the displacement of the fringe in changing at constant temperature the pressure of the cold gas until its density is equal to that of the gas in the warm arm which is at constant pressure.

Apparatus.—There is a difficulty arising from the necessity of separating the light into two parallel beams, then reuniting them without imparting a difference of phase
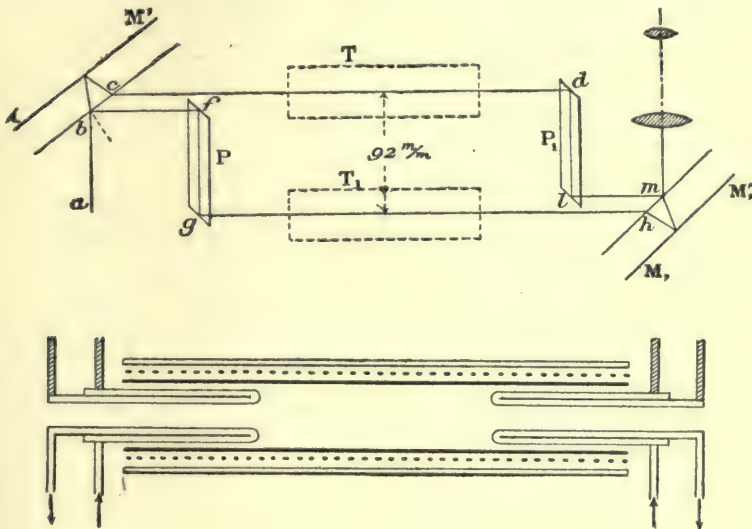
Fig. 9.

which renders the fringes invisible with white light. This is done in the following way (see Fig. 9):

A beam of light *ab* falls on a mirror *MM'*, which breaks it up into two parallel beams, *bf* and *cd*; in order to separate the beams so as to be able to place apparatus conveniently with respect to them, a prism *P* gives to the beam *bf* the direction *gh*; one can thus secure a separation of 92 mm. A second prism P_1 brings the beam *cd* into *lm*, and after reflection from a second mirror, M_1M_1', the

fringes are observed in a telescope focussed for parallel rays. The tubes containing the gases are placed at T and T_1.

It is evidently necessary that the prisms P and P_1 be perfectly made. A preliminary adjustment is made with yellow light, then it is perfected with white light.

The tube at variable pressure is closed by two pieces of plate glass, as is also the warm tube; these four plates should be absolutely alike. The warm tube is heated by a vapor-bath at low temperatures, by an electric current passing through a spiral at high temperatures.

But there is a difficulty in that in the warm tube there exists a region of variable temperature between the warm zone and the cold atmosphere.

To eliminate the influence of this variable zone there are inside the warm tube two tubes containing running cold water whose distance apart can be changed; it is assumed that the variable region remains the same, and that distance between the two tubes gives the warm column actually utilized. It follows that the comparative lengths of the warm column and of the cold column (this latter remaining constant) are not the same; the formula to be used will be somewhat more complicated.

n being the index of refraction of a gas and d its density, we have

$$n - 1 = kd.$$

In the constant-pressure tube

$$\frac{d_1}{d_0} = \frac{p}{p_0}.$$

To obtain the invariability of the fringes it is necessary that

$$(n_1 - n_0)L = (n' - n_0)l,$$

L being the length of the cold tube, and l the displacement of the warm tube;

$$k(d_1 - d_0)L = k(d' - d_0)l,$$

$$L\left(\frac{d_1}{d_0} - 1\right) = l\left(\frac{d'}{d_0} - 1\right),$$

$$L\left(\frac{p}{p_0} - 1\right) = l\left(\frac{T_0}{T} - 1\right),$$

an expression which gives a relation between the pressures and the temperatures.

This method, employed for the control of the boiling-points, has given the following results which are near those calculated from the old experiments of Regnault.

	Pressure.	Temperature Observed.	Temperature Calculated.
Alcohol................	741.5 mm.	77°.69	77°.64
Water................	740.1	99 .2	99 .20
"	761.04	100 .01	100 .01
Aniline................	746.48	183 .62	183 .54
"	760.91	184 .5	184 .28

Berthelot has standardized by the same method a couple which he used to determine the fusing-points of silver, copper, gold, and the boiling-point of zinc:

Silver............................	962°
Gold............................	1064
Zinc.	920
Cadmium...	778

Except for the zinc, the numbers found are identical with those which result from the best determinations made by other methods. The difference observed for the zinc is probably due to the radiation from the coverings of the vessel containing the metal.

Fixed Points.—The fixed points which will be employed for the graduation of other pyrometers should be chosen from among the temperature-determinations made with the gas-thermometer. Among those that we have ex-

amined, hardly others than the following are to be recommended:

Sulphur.—(Boiling) 445° under a pressure of 760 mm., with a variation of 0°.095 per millimeter change of mercury in the atmospheric pressure.

The boiling-point of sulphur has been the object of four series of distinct determinations:

Regnault	448°
Crafts	445
Callendar	444 .5
Chappuis and Harker	445 .2

Regnault's figure was obtained by plunging the reservoir of the thermometer in the liquid sulphur; this liquid can superheat and gives too high a number. The other three very concordant observations were obtained in the vapor. They lead to the mean value of 445°, which should be accurate to at least 0°.5.

Zinc.—(Boiling) 930°, with a variation of 0°.15 for a change of 1 mm. in the atmospheric pressure.

The boiling-point of zinc, as that of sulphur, has been the object of numerous observations:

E. Becquerel	930° and 890°
H. Sainte-Claire-Deville	915 to 945
Barus	926 and 931
Violle	929 .6
D. Berthelot	920

The values obtained by Violle and Barus which seem the most worthy of confidence lead to the adoption of the approximate value 930°, which should be exact to 5°.

We have omitted in the above table the determinations of H. Sainte-Claire-Deville made with the vapor of iodine and the carbonic-acid thermometer, which give figures 100° higher and are certainly much too high.

Gold. — (Fusion) 1065°. The determinations of the fusing-point of gold, also quite numerous, are still less concordant than those of the boiling-point of zinc.

Pouillet...................... 1180°
E. Becquerel................. 1092 and 1037°
Violle........................ 1045
Holburn and Wien............ 1070 to 1075
Heycock and Neville......... 1062
D. Berthelot................. 1064

The last four determinations *à priori* seem to merit an equal confidence. But the comparison between the fusing-point of gold by Violle, 1045°, and his fusing-point of silver, 954°, gives only a difference of 90°. On the other hand, by means of thermoelectric couples it is easy to establish with certainty that the difference between these two temperatures is greater than 100°, although not much above this figure. Besides, the experiments of Violle on the fusing-point of silver are among the best. On this basis, we would find 1060° for the fusing-point of gold.

By limiting ourselves to the last three series, we may take the approximate number 1065°, which should not have an error greater than 10°.

Silver.—(Fusion) 962°. The fusing-point of this metal is of a less advantageous use than that of gold, by reason of its volatility, which does not allow of heating it near platinum wires (thermoelectric couple), as it alters them decidedly, and also by reason of greater changeability of fusing-point. In reducing atmospheres in contact with siliceous matters, the fusing-point is lowered markedly, on account probably of an absorption of silicium, as happens with platinum.

The fusing-point of silver is one which has been the most often determined.

Pouillet	1000°
E. Becquerel	960 and 916°
Violle	954
Holborn and Wien	970
Heycock and Neville	960 .5
D. Berthelot	962

The last four determinations which seem to merit equal weight give a mean value of 962°, which should certainly be exact to at least 10°, very probably even to 5°.

Platinum.—1780°. The fusing-point of platinum has been determined twice by Violle in the first place, and then by Holborn and Wien. The results differed by only 1°, that is to say, they were practically identical. This accord, however, should be only considered as a lucky chance, which can give no indication of the accuracy of the determination of this fusing-point. The experimental measurements, and above all the indispensable extrapolations, involve greater uncertainties that cannot be known *à priori.* An error of 25° would not be incompatible with the precision of the measurements made.

Sometimes it is desired to graduate a pyrometer down to the temperature of the surroundings, even if in this case the use of the mercury-thermometer is to be preferred. Use may then be made of the two boiling-points of water and naphthalin.

Water.—100°, with a variation of 0°.04 for a change of 1 mm. in the atmospheric pressure.

Naphthalin.—218°, with a variation of 0°.06 for a change of 1 mm. in the atmospheric pressure.

Metallic Salts.—The different fixed points that have been mentioned are not all of a very convenient use. It would be preferable to have, in place of the metals, metallic salts for the determination of the fixed points. These salts in fact are for the most part without action

on platinum, which is a great advantage for the standard-
ization of thermoelectric couples. There are none, unfor-
tunately, whose fusing-points have been determined up to
the present time in a sufficiently precise manner.

Among the most interesting to study, from this point
of view, we may cite the following:

1 mol. NaCl + 1 mol. KCl.....................	About 650°
NaCl	" 800
$Na_2O.SO_3$.....................................	" 900
$Pb_2O_3.2Na_2O$................	" 1000
$MgO.SO_3$...........	" 1150
$SiO_2.CaO$	" 1700

Table of Fixed Points.—In the actual state of our
knowledge the fixed points to which we should give prefer-
ence are summarized in the table below:

	Ebullition.	Fusion.
Water......................	100°	
Naphthaline................	218	
Sulphur....................	445	
Zinc.......................	930	
Silver.....................	....	962°
Gold.......................	....	1065
Platinum.	....	1780

CHAPTER IV.

CALORIMETRIC PYROMETRY.

Principle.—A mass p of a body, brought to a temperature T, is dropped into a calorimeter containing water at a temperature t_0. Let t_1 be the final temperature of water and substance. P being the water-equivalent of the substances in contact (water, calorimetric vessel, thermometer, etc.) which are raised from t_0 to t_1, L_t^T the heat required to warm unit mass of the body from t_1 to T, we have

$$L_t^T \times p = P(t_1 - t_0).$$

Taking as origin of temperatures the zero of the centigrade thermometer, the heat required to warm unit mass of the body to the temperature T will be

$$L_t^T = L_{t_1}^T + L_0^t.$$

The quantity L_{0t} is easy to calculate, because the specific heats at low temperatures are sufficiently well known:

$$L_0^t = ct_1.$$

The expression for the total heat becomes

$$L_0^T = \frac{P(t_1 - t_0)}{p} + ct_1.$$

t_1 and t_0 are the temperatures given by the direct readings of the thermometer.

The value of the second member is thus wholly known, and consequently that of the first member which is equal

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to it. If previous experiments have made known the value of the total heat L_0^T for different temperatures, one may from the knowledge of L_0^T determine the value of T. It will be sufficient to trace a curve on a large scale whose abscissas are temperatures, and ordinates total heats, and to find upon this curve the point whose abscissa has the value given by the calorimetric experiment.

Choice of Metal.—Three metals have been proposed: *platinum*, *iron*, and *nickel*.

Platinum.—This metal was first proposed by Pouillet, and taken up again by Violle. It is much to be preferred to the other metals; its total heat has been compared directly with the indications of the air-thermometer. This metal can be probably reproduced identical with itself. Iridium, which commercial platinum often carries, has the same specific heat. The high price of these substances is an obstacle to their use extensively in works; for a calorimeter of a liter it is necessary to have at least 100 grms. of platinum,—or \$100 in a volume of 5 cc.,—easily lost or made away with.

Violle determined the total heat of platinum from 0° to 1200°, and computed by extrapolation up to 1800°.

100°	3.23 cal.	1000°	37.70 cal.
200	6.58	1100	42.13
300	9.75	1200	46.65
400	13.64	1300	51.35
500	17.35	1400	56.14
600	21.18	1500	61.05
700	25.13	1600	66.08
800	29.20	1700	71.23
900	33.39	1800	76.50

Iron.—Regnault, in a study made for the Paris Gas Company, had proposed, and caused to be adopted, iron, in attributing to it a specific heat of 0.126, while it is, at 0°, 0.106. He used a cube of 7 cm. sides which was thrust

into the furnaces by means of long iron bars.   The calorimeter was of wood and had a capacity of 4 liters.

Various observers have determined the total heat of iron; at high temperatures the accord is not perfect among the results.

Temperature.	Post.	Pionchon.	Euchène.	Mean Specific Heat.
Degrees.	Calories.	Calories.	Calories.	Calories.
100	10.8	11.0	11.0	10.8
200	22.0	22.5	23.0	21.5
300	35.0	36.5	37.0	32.5
400	39.5	41.5	42.0	43.0
500	67.5	68.5	69.5	54.0
600	86.0	87.5	84.0	65.0
700	108.0	111.5	106.0	76.0
800	132.0	137.0	131.0	87.0
900	157.0	157.5	151.5	98.0
1000	187.5	179.0	173.0	109.0

But this metal is not at all suitable for such use, by reason in the first place of its great oxidability.   There is formed at each heating a coating of oxide which breaks off upon immersion in water, so that the mass of the metal varies from one observation to the next.   Besides, iron, especially when it contains carbon, possesses changes of state accompanied during the heating by a marked absorption of heat.   By cooling in water, tempering takes place which may irregularly prevent the inverse transformations.

Nickel.—At the Industrial Gas Congress in 1889 Le Chatelier proposed nickel, which is but slightly oxidizable up to 100°, and which above 400° does not possess changes of state as does iron.

The total heat of nickel has been determined by Pionchon and by Euchène and Biju-Duval.

The differences are due very probably in part to impurities that the nickel may contain.

Temperature.	Pionchon.	Euchène.
Degrees.	Calories.	Calories.
100	11.0	12.0
200	22.5	24.0
300	42.0	37.0
400	52.0	50.0
500	65.5	63.5
600	78.5	75.0
700	92.5	90.0
800	107.0	103.0
900	123.0	117.5
1000	138.5	134.0

Calorimeters.—1. In laboratories there is employed with the platinum mass Berthelot's calorimeter, a description of which is given in the *Annales de Chemie et de Physique* * (Fig. 10). The thermometer used for the
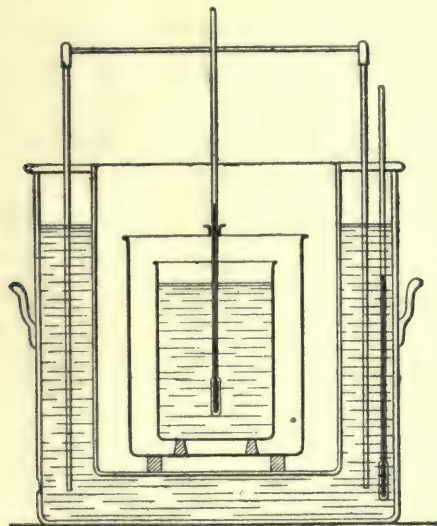

FIG. 10.

measurement of the rise in temperature should be very sensitive, so that a rise of from 2° to 4° be sufficient in

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* 4th Series, t. XXIX. p. 109 ; 5th Series, t. V. p. 5 ; t. X. p. 433 and 447 ; t. XII. p. 550.

order to render negligible the cooling correction. If use is made, for instance, of a thermometer giving the hundredth of a degree, the mass of platinum should be about one-twentieth the mass of the water in the calorimeter.

2. In the arts, where the measurements are made with less precision, and where it is necessary to consider the cost of installation of the apparatus, nickel will be made use of, a thermometer giving tenths of a degree, and a zinc calorimeter, which may be home-made. Such an installation may cost as little as $4. A mass of nickel should be used equal to one-twentieth of the mass of water of the calorimeter.

The calorimeters used by the Paris Gas Company are after the Berthelot pattern. They are also water-jacketed calorimeters, of which there are two types.

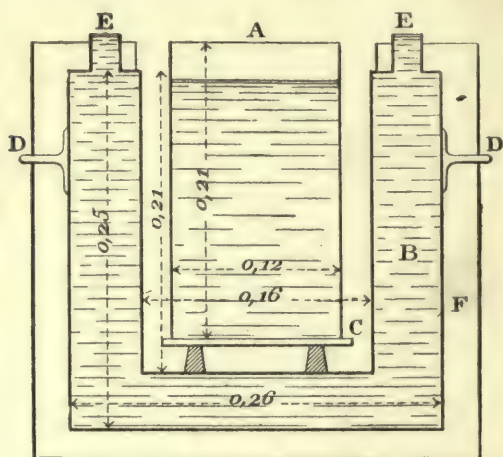*Water-jacketed Calorimeters.* (Figs. 11 and 12).—These

FIG. 11.

A, cylindrical vessel of thin copper ; *B*, water-jacket ; *C*, wooden support ; *D*, handles ; *E*, filling-tubes ; *F*, felt jacketing.

apparatus consist of a cylindrical calorimeter of two liters capacity, of zinc or of copper; a double cylindrical jacket

of the same metal, containing water and surrounded by felt on the outside. The calorimeter rests on this jacket by means of a wooden support. A thermometer graduated to
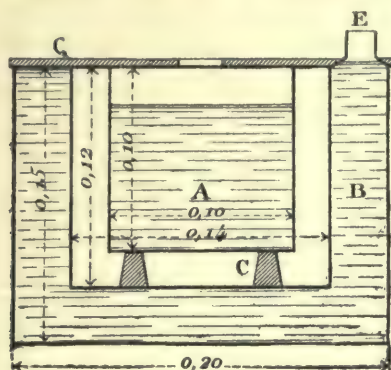

FIG. 12.

A, zinc vessel ; *B,* water-jacket ; *C*, cork supports ; *E*, filling-tube ; *G*, cardboard cover.

fifths of a degree, having a small but quite long bulb, serves as stirrer. The thermometric substance is a piece of nickel of mass equal to one-tenth that of the water, or 200 grms., so as to have considerable rise of temperature easy to read by the workmen who make the measurements.

As a general rule, one must avoid placing the thermometric substance upon the floor of the furnace. The piece of nickel, which is made in the form of small cylinders having from 15 to 25 mm. diameter and from 10 to 30 mm. length, rests so as to be insulated from the floor in a nickel crucible provided with a foot and with two arms attached somewhat above the centre of gravity. When it has been heated for a half-hour an observer takes out the crucible with a forked rod, and another

FIG. 13.

seizes this crucible with tongs to empty it into the calorimeter.

Use is not made of an iron crucible because this metal

oxidizes and lets drop scales, which falling into the calorimeter would vitiate the experiment. Inside of a nickel crucible one can use pieces of fire-clay of the above form (Fig. 13).

Precision of the Measurements.—Biju-Duval has made a series of experiments to study the sources of error arising from the use of the calorimeter by comparing its indications to those of the thermoelectric pyrometer of Le Chatelier. The observations were taken by varying the following conditions:

Use of thermometer graduated to $\frac{1}{5}$° or to $\frac{1}{50}$°.

Use of the old wooden gas-works calorimeter or of the water-jacketed calorimeter.

Use of iron or nickel.

I. *Experiment.* — Old wooden gas-works calorimeter. Iron. Thermometer in fifths.

$$P = 10000 \text{ grm.}$$
$$p = 1031 \text{ ``}$$
$$t_0 = 20°.8$$
$$t_1 = 36°.2$$
$$Q_0^t = 153.5 \text{ cal.}$$

Computed temperature:

Mean specific heat of iron = 0.108 $t = 1420°$
"   "   "   "   " = 0.126 $t = 1210$
Heat-toning according to Biju-Duval   = 915
Thermoelectric pyrometer   = 970

It is thus evident that the mean specific heats even with the correction suggested by Regnault give temperatures much too high. With the curve of total heats the temperature found is much too low on account of the following losses of heat:

1. Absorption of heat by the wooden walls;

2. Radiation from the iron cube during transfer;

3. Cooling of the water in the calorimeter, whose temperature exceeded by 16° the temperature of the surroundings.

The following experiments were made with the thermometer reading to $\frac{1}{50}°$; the piece of nickel was protected against radiation by a crucible. The two calorimeters were compared.

II. *Trial with the Wooden Calorimeter.*

$T = 975°$ by the thermoelectric pyrometer
$P = 10000$ grm.
$p = \quad 145 \quad$ "
$t_0 = 20°.21$
$t_1 = 21°.99$
$L_0{}^T = 125$ cal.
$L_0{}^T = 130$ cal. from the curve at 975°

The difference is 5 calories, or 4 per cent loss due to the jacket.

III. *Trial with the Water-jacketed Calorimeter.*

$T = 985°$
$P = 2000$ grm.
$p = 48.4 \quad$ "
$t_0 = 18°.86$
$t_1 = 21°.95$
$L_6{}^T = 130$ cal.
$L_0{}^T = 131.5$ cal. from the curve at 985°

The difference is 1.5 calories, or a loss of only 1.11 per cent when use is made of a carefully made calorimeter and of a thermometer giving $\frac{1}{50}°$. This corresponds to an uncertainty of less than 10° in the temperatures sought. With the $\frac{1}{10}°$ thermometers, necessitating a much greater rise of temperature of the water in the calorimeter, an uncertainty of 25° will exist.

Conditions of Use.—The advantages of the calorimetric pyrometer are:

1. Its low net cost;

2. The ease of its use, which allows of putting it in the hands of a workman.

Its inconveniences are:

1. The time necessary to take an observation, about a half-hour;

2. The impossibility of taking continuous observations;

3. The impossibility of exceeding 1000° by the use of the piece of nickel.

Its use does not seem to be recommendable for laboratories.

It is to be recommended for works in the cases where it is required to make only occasional measurements; in cases where there is not the personnel sufficiently skilful to use the more precise methods; and finally where the importance of the measurements is not such as to justify the buying of more costly instruments.

CHAPTER V.

ELECTRICAL RESISTANCE PYROMETER.

Principle.—In this apparatus use is made of the variations of electric resistance of a platinum wire as a function of the temperature; these variations are of the order of magnitude of those of the expansion of gases. The ratio of the resistances is 1.34 at 100°, and 4 at 1000°. As electric resistances are measurable with great accuracy, this process of estimation of temperatures offers a very great sensibility, and it will be able to give very good results when we know exactly the law that connects the variations of resistances to those of temperature.

The electric pyrometer was proposed by Siemens in 1871 (Bakerian Lecture); it rapidly came into use in metallurgical works on account of the reputation of its inventor, but it was soon abandoned for reasons which will be given later.

Investigations of Siemens.—The Siemens pyrometer consists of a fine platinum wire 1 m. long and 0.1 mm. in diameter, wound on a cylinder of porcelain or fire-clay; the whole is enclosed in an iron tube, destined to protect the instrument from the action of the flames.

Siemens tried also, but without success, ceramic matters impregnated with metals of the platinum group.

To measure resistance he employed either a galvanometer, for laboratory experiments, or a voltameter, for the measurement in works. In this latter case the current from a cell divides between the heated resistance and a standard resistance at constant temperature; in each one

of the circuits was placed a voltameter: the ratio of the volumes of gas set free gives the ratio of the current strengths and thus the inverse ratio of the resistances.

Finally Siemens gave a formula of three terms connecting the electrical resistance of platinum to temperatures on the air-thermometer, but without publishing the experimental data on which this graduation was based.

Experiment soon showed that the apparatus did not rest comparable with itself. A committee of the British Association for the Advancement of Science found that the resistance of platinum increases after heating. It would be necessary then to graduate the apparatus each time that it was used. This change of resistance is due to a chemical alteration of platinum, which is enormous when directly heated in the flame, less, but still marked, if placed in an iron tube, and which disappears if use is made of a platinum or porcelain tube. This augmentation of resistance may reach 15 per cent by repeated heatings up to 900°.

Platinum being very costly and porcelain very fragile, it was impossible to use these two bodies in the industries, which alone at that time occupied themselves with measurements of high temperatures, and this method was abandoned completely during twenty years.

Investigations of Callendar and Griffiths.—These savants have revived this method for laboratory purposes; it seems the best for work of precision, on the condition of being assured of the invariability of the resistance of platinum.

Callendar found that clay helps to cause the variation of resistance, that the platinum wire becomes brittle on its support and sticks there; this action is probably due to impurities in the clay. With mica, on the other hand, which the wire touches only at the edges (the reel is made

of two perpendicular slices of mica), there is perfect insulation without cause of alteration; but mica becomes dehydrated at 800° and then becomes very fragile.

All *metallic solderings* should be proscribed, for they are volatile and attack platinum.

Pressure joints (screw or torsion) are equally bad, for they become loose. One should use only the "autogène" solder by the fusion of platinum.

Copper conductors should also be rejected, at least in the heated portions, on account of the volatility of the metal. A pyrometer with such conductors, heated during an hour at 850°, showed an increase of resistance of $\frac{1}{3}$ per cent.

Investigations of Holborn and Wien.—These savants have made a very complete study of this alterability of platinum wires, in a comparison between the methods of measurement of temperatures by electric resistance and thermoelectric forces; they work with wires of 0.1 mm. to 0.3 mm. diameter. They soon found that above 1200° platinum commences to undergo a feeble volatilization which suffices to augment notably the resistance of the very fine wires. Hydrogen in presence of silicious matters causes about 850° a rapid alteration of the platinum.

Below are the results relative to wires of 0.3 mm. of a length of 160 mm.

Wire α.	R at 15°.	Wire β.	R at 15°.
At start...........	0.239 ohm	At start.............	0.247 ohm
After heating red-hot:		After several days in	0.246 "
Twice in air at 1200°	0.238 "	hydrogen at 15°	
Once in vacuo "	0.240 "	After heating in hydrogen to 1200°	0.255 "
" "hydrogen "	0.262 "		
" "vacuo "	0.253 "		

Wire γ.	R at 15°
At start...........................	0.183 ohm
After heating in air to 1250° (three times)	0.182 "
" " " H " "	0.188 "
" " " " " "	0.195 "

Wire γ heated to 1350° in an earthenware tube and in hydrogen became brittle; this result may be explained by a siliciuration of the platinum, for there is nothing observed if the wire is heated by the electric current in the interior of a cold glass tube, even in hydrogen. Similar experiments were made by the same observers with palladium, rhodium, and iridium.

With *palladium* the absorption of hydrogen at low temperatures, giving the hydride, increases the resistance by 60 per cent; besides, the same effect of alteration as with platinum is noticed if the palladium is placed in hydrogen in presence of silicium.

There is no definite conclusion to be drawn from the experiments with rhodium and iridium, except that these metals assume their normal resistance only after having been heated several times to a high temperature.

Law of the Variation of Platinum Resistance.—Callendar and Griffiths have compared the resistance of platinum with the air-thermometer up to 550°; they found that up to 500° the relation could be represented at least to 0°.1 by a parabolic formula of three parameters. In order to graduate such a pyrometer it would be sufficient then to have three fixed points: ice, water, sulphur.

They gave a special form to the relation; let p be the electric temperature defined by the relation

$$p_t = \frac{R_t - R_0}{R_{100} - R_0} \cdot 100,$$

that is to say, the value of the temperature in the case in which the resistance varies proportionally to the temperature.

They then placed

$$t - p_1 = \delta \left[-\frac{t}{100} + \left(\frac{t}{100} \right)^2 \right].$$

It would appear as if this formula contained the single parameter δ; but in reality p_t includes two.

Substituting for p its value, we have

$$R_t = R_0 t + \frac{(1+\delta)(R_{100} - R_0)}{(100)^2} \cdot t - \delta \frac{R_{100} - R_0}{(100)^3} \cdot t^2,$$

an equation of the form

$$R_t = a + bt + ct^2.$$

This complicated form is without interest. Callendar and Griffiths used their pyrometer before having standardized it against the air-thermometer. Not being able to compute t, they provisionally computed the approximate temperatures p_t, and later determined the correction between t and p_t, after having sought the formula expressing the difference between these two quantities. By extrapolation up to 1000° the points of fusion of gold and of silver were found quite near to those determined by other observers.

Holborn and Wien have shown, however, that at a high temperature the interpolation formula is certainly inexact. The resistance seems to become asymptotic to a straight line, while the formula leads to a maximum evidently inacceptable; it would be without doubt better represented by an expression of the form

$$R \cdot t = a + b(t + 273)^m.$$

Here are the results of several experiments made on the same wire by these two savants:

t. Degrees.	R. Ohms.	t. Degrees.	R. Ohms.
0	0.0355	0	0.0356
1045	.1510	1040	.1487
1193	.1595	1144	.1574
1303	.1699	1328	.1720
1395	.1787	1425	.1802
1513	.1877	1550	.1908
1578	.1933	1610	.1962

This wire came in contact with the furnace-gases, as a result of breaking the tube, and was broken. Another wire gave the following results:

t.	R.
567°	0.0972 ω
772	.1164
1045	.1408
1185	.1511
1263	.1573

Experimental Arrangement (Fig. 14).—In Callendar's pyrometer the platinum wire is wound on two strips of mica set crosswise. Three heavy platinum wires serve to lead in and out the current; one of them is to compensate for the influence of temperature along the parallel conductor.

FIG. 14.

In the laboratory the resistance measurements are made by a Wheatstone's bridge (Fig. 15). A resistance-box is used, furnished also with a rheostat consisting of a stretched platinum wire serving to measure the small fractions of resistance.

In industrial practice use is made of an apparatus (Fig. 15 *bis*) composed of a needle-gavanometer and a resistance-box of circular form, consisting of fifteen spools of 1 ohm. The deflection corresponding to two successive contacts is read, and by interpolation is found the real value of the resistance. The approximation thus obtained is sufficient.

To avoid breaking, the pyrometer should be installed in advance in the cold furnace, or heated previously in a muffle if it is necessary to

introduce it into the hot furnace. It is necessary to take care and heat the porcelain throughout sufficient of its length in order to avoid the effect of the interior conductibility, which would prevent the spiral taking the temperature of the surrounding medium.
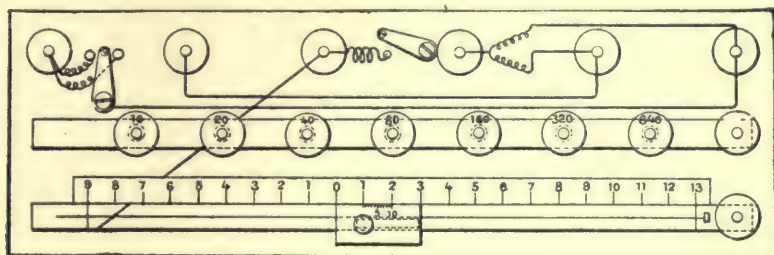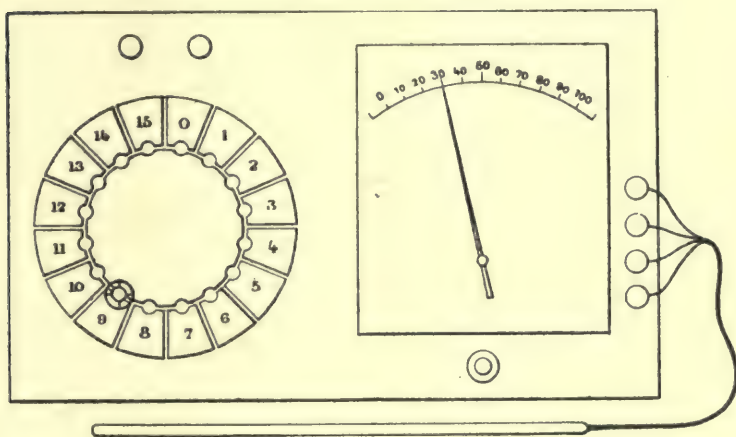

FIG. 15.

FIG. 15 *bis*.

Callendar and Griffiths have determined a certain number of fusing- and boiling-points:

Fusion.		Ebullition under 760 mm.	
Tin................	232°	Aniline........	184°.1
Bismuth............	270	Naphthaline........	217 .8
Cadmium	322	Benzophenone	305 .8
Lead................	329	Mercury............	356 .7
Zinc	421	Sulphur............	444 .5

We may compare these results with the anterior determinations of Crafts with the air-thermometer.

Naphthaline.		Benzophenone.	
p.	*t.*	*p.*	*t.*
Millimeters.	Degrees.	Millimeters.	Degrees.
730.3	216.3	730.9	304.2
740.3	216.9	740.1	304.8
750.5	217.5	750.9	305.5
760.7	218	760.3	306.1

Regnault had found for mercury:

$t = 350°$ under a pressure of.................. 663 mm.
$t = 360$ " " " ".................. 797.7 "
$t = 370$ " " " ".................. 954.6 "

Heycock and Neville have applied the method previously described, in prolonging the graduations, by extrapolation, to the determination of the fusing-points of several metals and salts:

Metals
- Tin.................................... 232°
- Zinc.................................. 419
- Magnesium (1 per 100 of impurities)...... 633
- Antimony............................ 629 .5
- Aluminium (0.5 per 100 of impurities).... 654 .5
- Silver................................ 960 .5
- Gold................................. 1062
- Copper............................... 1080 .5

Salts
- Potassium sulphate ...... 1084° (fusion) / 1067 (solidification)
- Sodium sulphate......... 902 (fusion) / 883 (solidification)
- Sodium carbonate....... 850

The difference found between the points of fusion and of solidification of potassium sulphate is explained by the presence of a dimorphic point of transition in the neighborhood of the fusing-point. It is a case analogous to that of sulphur; there is observed, according to the case, the

point of fusion or solidification of the one or the other dimorphic variety. It is without doubt the same in the case of the sodium sulphate.

Conditions of Use.—The electrical resistance pyrometer seems, by reason of the great precision of the measurements which it allows, to be especially serviceable for laboratory investigations. It seems on the other hand to be too fragile for the greater part of the industrial applications.

In any case, before it can be employed usefully at high temperatures, it will be necessary that the determination of the resistance of platinum, made only to 600° in a not over-precise manner, be pushed further.

CHAPTER VI.

THERMOELECTRIC PYROMETER.

Principle.—The junction of two metals heated to a given temperature is the seat of an electromotive force which is a function of the temperature only, at least under certain conditions which we shall define further on. In a circuit including several different junctions at different temperatures the total electromotive force is equal to their algebraic sum. In a closed circuit there is produced a current equal to the quotient of this resultant electromotive force and the total resistance.

It was Becquerel who first had the idea to profit from the discovery of Seebeck to measure high temperatures (1830). He used a platinum-palladium couple, and estimated the temperature of the flame of an alcohol lamp, finding it equal to 135°. In reality the temperature of a wire heated in a flame is not that of the gases in combustion; it is inferior to this.

The method was studied and used for the first time in a systematic manner by Pouillet; he employed an iron-platinum couple which he compared with the air-thermometer previously described (page 50). In order to protect the platinum from the action of the furnace-gases, he enclosed it in an iron gun-barrel which constituted the second metal of the junction. Pouillet does not seem to have made applications of this method, which must have given him very discordant results.

Edm. Becquerel resumed the study of his father's couple (platinum-palladium). He was the first to remark the great importance of using in these measurements a galvanometer of high resistance. It is the electromotive force which is a function of the temperature, and it is the current strength that is measured. Ohm's law gives

$$E = RI.$$

In order to have proportionality between these quantities, it is necessary that the resistance of the circuit be invariable. That of the couple necessarily changes when it is heated; this change must be then negligible in comparison with the total resistance of the circuit.

Edm. Becquerel studied the platinum-palladium couple and made use of it as intermediary in all his measurements on fusing-points, but he did not use it, properly speaking, as a pyrometer; he compared it, at the instant of observation, with an air-thermometer heated to a temperature near to that which he wished to measure. He also tried to make a complete graduation of this couple, but this attempt was not successful; he did not take into account the irregularities due to the use of palladium; besides, he made use successively for this graduation of a mercury-thermometer and of an air-thermometer which did not agree with each other. He was led to assume for the relation between the temperature and the electromotive force a very complex expression; the formulæ which he gives contain together twelve parameters, while with the parabolic formula of Tait and Avénarius two suffice; thus

$$e = u + b(t - t_0) + c(t^2 - t_0^2),$$

which well represents the phenomenon for the couple in question up to 1500°.

Regnault took up the study of Pouillet's couple, and he observed such irregularities that he condemned unreservedly

the thermoelectric method. But these experiments are hardly conclusive, for he does not seem to have considered the necessity of using a high-resistance galvanometer.

Experiments of Le Chatelier. — The thermoelectric method possesses nevertheless very considerable practical advantages for use in the laboratory as well as industrially, such as

Smallness of thermoelectric substance;

Rapidity of indications;

Possibility of placing at any distance the measuring apparatus.

Also Le Chatelier decided to take up the study of this method, intending at the outset not to make disappear the irregularities which seemed inherent to the phenomena in question, but to study the law of these irregularities, so as to determine corrections which would permit of making use of this method, at least industrially, for approximate measurements. These investigations showed in their turn that the sources of error observed could be suppressed; the principal one, and the only serious one, came from the lack of homogeneity of the metals up to that time employed.

Iron, nickel, palladium, and their alloys are absolutely unsuited for the measurement of high temperatures, because, heated in certain of their points, they give birth to parasite currents, sometimes relatively intense.

Heterogeneity of Wires.—Here, for example, are the electromotive forces observed in carrying a Bunsen flame along beneath a wire of ferro-nickel of 1 mm. diameter and 50 cm. long; the electromotive forces are expressed in microvolts (millionths of a volt).

Distance...	0.05	0.10	0.15	0.20	0.30	0.35	0.40	0.50
E. M. F....	−200	+250	−150	−1000	−500	−200	−50	−200

An electromotive force of 1000 microvolts is that given by the usual couples that we are going to study for a heat-

ing of 100°. With such anomalies as above there could hardly be any measurements possible.

These anomalies may sometimes be due to acccidental variations in the composition of the wires, but in general there is no pre-existing heterogeneity; a physical heterogeneity due to the heating is produced. Iron and nickel, heated respectively to 750° and 380°, undergo an allotropic transformation, incompletely reversible by rapid cooling.

In the case of palladium there is produced, besides, phenomena of hydrogenation which change completely the nature of the metal, so that a metal initially homogeneous may become by simple heating quite heterogeneous and form a couple.

Certain metals and alloys are absolutely free from these faults, notably platinum and its alloys with iridium and rhodium. The irregularities previously observed are thus due to the employment of iron and palladium in all the couples tried.

A second source of error, less important, comes from the annealing. In heating a wire at the dividing-point between the hardened part and the annealed part there is developed a current whose strength varies with the kind of wire and the degree of hardness. The twisting that a wire has undergone at a point suffices to produce a hardening. A couple whose wires are hard drawn throughout a certain length will give different indications according to the point of the wire where the heating ceases. Here are results in microvolts obtained with a platinum platinum-iridium (20 per cent I_2) couple (platinum-iridium alloy is very easily hardened).

	100°	445°
Before annealing	1100	7200
After annealing	1300	7800
Difference	200	600

We shall study successively:

1. The choice of the couple;
2. The choice of methods of measurement;
3. The sources of error;
4. The standardization.

Choice of the Couple.—Account must be taken of the electromotive force, the absence of parasite currents, the inalterability of the metals used.

a. Electromotive Force.—This varies enormously from one couple to another. Below are several such electromotive forces given between 0° and 100° by metals that can be drawn into wires and opposed to pure platinum.

	Microvolts.
Iron	2100
Hard steel	1800
Silver	900
Cu + 10% Al	700
Gold	600
Pt + 10% Rh Pt + 10% Ir	500
Cu + Ag	500
Ferronickel	100
Nickel-steel (5% Ni)	0
Manganese steel (13% Mn)	− 300
Cu + 20% Ni	− 600
Cu + Fe + Ni	−1200
German silver (15% Ni)	−1200
" " (25% Ni)	−2200
Nickel	−2200
Nickel-steel (35% Ni)	−2700
" " (75% Ni)	−3700

Barus* studied certain alloys between 0° and 930°; he obtained the following results:

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* Barus, at the same time as Le Chatelier, studied the thermo-electric measurement of high temperatures; he sought to determine the temperatures of formation of the rocks of the earth's crust; his very considerable investigations are little known. There is a great mass of numerical data in his work, use of which will be made here.

Microvolts.

Iridium (2%).......... 791
"   (5%)................................ 2830
"   (10%).............................. 5700
"   (15%).............................. 7900
"   (20%).............................. 9300
Palladium (3%)............................   982
"   (10%)............................. 9300
Nickel (2%)................................ 3744
"   (5%)............................... 7121

Here is another series made at the boiling-point of
sulphur with alloys of platinum containing 2, 5, and 10
per cent of another metal:

Metals.	Au	Ag	Pd	Ir	Cu
2%	− 242	− 18	+ 711	+1384	+410
5	− 832	−105	+ 869	+2035	+392
10	−1225	−158	+1127	+3228	+257

	Ni	Co	Fe	Cr	Sn	Zn
2%	+2166	+ 26	+3020	+2239	+261	+396
5	+3990	−170	+3313	+3123	+199	+ 24
10	+5095	− 41	+3962	+3583	+151	

	Al	Mn	Mo	Pb	Sb	Bi
2%	+779	+ 758	+ 263	−268	+1155	+245
5	+938	+2206	+1673	+338		
10	....	....	+ 766			

Of all these metals, the only ones to keep by reason of
their high electromotive force are the alloys of platinum
with iron, nickel, chromium, iridium, and rhodium. The
following table gives, in microvolts, the electromotive
forces of the 10 per cent alloys of these five metals up to
the temperature of 1500°;

Temperatures.	Fe	Ni	Cr	Ir	Rh
100°	438	646	405	517	565
448	3962	4095	3583	3228	3450
930	9200	9100	. . . .	11000	8500
1500	19900	20200	. . . .	. . . .	15100

b. Absence of Parasite Currents.—The alloy with nickel gives parasite currents of great intensity, as do all the alloys of this metal. It would be probably the same with iron, but there are no data on the matter. Chromium does not seem to present the same inconvenience: it forms an alloy difficult to fuse and, for this reason, difficult to prepare. With the alloys of iridium and of rhodium there is no production of parasite current.

There remain, then, but three metals to consider: iridium, rhodium, and chromium. Of the alloys of these metals with platinum, that of iridium is the one which hardens the most easily.

c. Chemical Changes.—All the alloys of platinum are slightly alterable. Those of nickel and of iron, at high temperatures, assume a slight superficial brownish tint caused by oxidation of the metal. No test has been made to see if, after a long time, this attack would reach even to the interior of the wires.

The alloys of platinum, and platinum itself, become brittle by simply heating them long enough, especially between 1000° and 1200°; this is due without doubt to crystallization. The platinum-iridium alloy undergoes this change much more rapidly than the platinum-rhodium, and this latter more rapidly than pure platinum.

But a much more grave cause of the alteration of platinum and its alloys is the heating to high temperatures in a *reducing atmosphere.*

All the volatile metals attack platinum very rapidly, and

a great number of metals are volatile. Copper, zinc, silver, antimony, at their points of fusion, already emit a sufficient quantity of vapor to alter rapidly the platinum wires placed in the neighborhood. These metallic vapors, that of silver excepted, can only exist in a reducing atmosphere. Among the metalloids, the vapors of phosphorus and of certain compounds of silicium are particularly dangerous. It is true that one is rarely concerned with these uncombined metalloids, but their oxides in the presence of a reducing atmosphere are more or less completely reduced. In the case of phosphorus it is not only necessary to shun phosphoric acid, but also acid phosphates of all the metals and the basic phosphates of the reducible oxides; for silicium, silica and almost all the silicates, clay included, must be avoided.

The reducing flames in a fire-clay furnace lead little by little to the destruction of the platinum wires. It is thus indispensable to protect the couples against any reducing atmosphere by methods which will be indicated further on.

In taking account of these different considerations, electromotive force, homogeneity, hardness, alterability by fire, we are led to give the preference to the couple $Pt - Pt + 10\%$ Rh, with the possibility of replacing the rhodium by iridium and perhaps by chromium. In the case of iridium it is necessary to recall that the preliminary annealing of the wires is very important, and that prolonged heating near 1100°, even in an oxidizing atmosphere, is dangerous for the couple.

Methods of Electric Measurements.—Two methods may be used to measure the electromotive force of a couple: the method by compensation and the galvanometric method. From the scentific point of view, the first alone is rigorous; it is sometimes made use of in laboratories. The second method is simpler, but possesses the inconvenience of giving

only indirectly the measure of the electromotive force by means of a measurement of current strength.

Compensation Method.—A complete installation consists of:

1. A *standard cell,* which should not have any current pass through it, and serves to determine, as term of comparison, a difference of potential between two points of a circuit through which there is a current given by an accumulator. The cell used is the Latimer-Clark, whose electromotive force is

$$e = 1.438 \text{ volt} - 0.0012(t° - 15°).*$$

This cell is made up as follows: zinc, sulphate of zinc, mercurous sulphate, mercury. The zinc sulphate should be perfectly neutral; for that the saturated solution of the salt is heated to 40° or more with an excess of zinc oxide to saturate the free acid, is then treated with mercurous sulphate to remove the excess of zinc oxide dissolved in the sulphate, and finally cyrstallization is produced at 0°; one thus obtains crystals of zinc sulphate which can be immediately used.

This element is very constant. With a surface of zinc electrode equal to 100 sq. cm. and a resistance of 1000 ohms, the dropping off of the electromotive force of the cell in action does not reach $\frac{1}{1000}$; with 100 ohms only, this would be $\frac{1}{200}$. Practically it is possible, with a resistance of 1000 ohms, to limit the surface of the electrodes to 30 sq. cm., and to do away with the use of accumulators. But then the theoretical advantage of the absolute rigor of the method employed is lost.

2. A *resistance-box* which includes a fixed resistance of about 1000 ohms and a series of resistances of 0 to 10 ohms, permitting by their combinations to realize in this interval resistances varying by tenths of an ohm. One may, for

---

* $e = 1.434[1 - 0.00080(t° - 15°)]$.

greater simplicity, but by sacrificing precision, replace this series of small resistances by a single Pouillet's rheostat having a total resistance of 10 ohms. This apparatus consists of two parallel wires of a meter in length and 3 mm. in diameter, made of an alloy of platinum and 3% copper.

3. A *sensitive galvanometer* giving an appreciable deflection for 10 microvolts. It is placed in the circuit of the couple. Use may be made here of a galvanometer Deprez-d'Arsonval of small resistance, since this is a case of reduction to zero.

In order to make an experiment, one places by trial the two extremities of the couple in contact with two points of the circuit of the cell chosen so that the couple is not traversed by any current.

In these conditions the electromotive force of the couple is equal and of opposite sign to the difference of potential between the two points of the circuit, and this, in calling

E the electromotive force of the cell,

R the total resistance of the circuit,

r the resistance between the two points considered, has for value

$$e = E \cdot \frac{r}{R} \cdot$$

Galvanometric Method.—The measurement of an electromotive force may be reduced to that of a current; it suffices for that to put the couple in a circuit of known resistance, and from Ohm's law we have

$$E = \frac{I}{R} \cdot$$

If the resistance is not known, but is constant, the electromotive force will be proportional to the current strength, and that will suffice, on the condition that the graduation of the couple is made with the same resistance. If this

resistance is only approximately constant, the relation of proportionality will be only approximately exact.

Resistance of Couples.—The wires of the couple make necessarily a part of the circuit in which the current strength is measured, and their resistance varies with increase of temperature. It is important to take account in the first place of the order of magnitude of this inevitable change of resistance.

Barus has made a systematic series of observations on the alloys of platinum with 10 per cent of other metal. The relation between the resistance and the temperature being of the form

$$R_t = R_0(1 + \alpha t),$$

he obtained the following results:

	Pt (pure)	Au	Ag	Pd	Ir	Cu	Ni	Fe	Cr	Sn
Specific resistance in microhms (R).	15.3	25.6	34.8	23.9	24.4	63.9	33.7	64.6	42	39
1000α..............	2.2	1	0.7	1.2	1.2	0.2	0.9	0.4	0.5	0.7

Other tests gave the figures below:

	5% Al	5% Mn	10% Mo	5% Pb	2% Sb	5% Bi	2% Zn	5% Zn
R_0...................	22	50	17.6	7.7	29.5	16.6	47.8	25
1000α..............	1.5	0.4	1.9	1.8	1	2	0.3	1.1

The coefficient α is taken between 0° and 357° (boiling-point of mercury).

The experiments of Le Chatelier, for the couples that he uses, gave the following results:

For platinum

$$R = 11.2(1 + 0.002t) \text{ between } 0° \text{ and } 1000°.$$

For rhodium-platinum (10% Rh)

$R = 27(1 + 0.0013t)$ between 0° and 1000°.

Holborn and Wien found for pure platinum

$R = 7.9(1 + 0.0031t)$ between 0° and 100°,

$R = 7.9(1 + 0.0028t)$ between 0° and 1000°.

In the greater number of cases use is made of couples 1 m. in length, whose wires are 0.5 mm. in diameter; their resistance, which is about 2 ohms cold, is doubled at 1000°. If use is made then of a galvanometer of a resistance of 200 ohms and if the variation of the resistance of the couple is neglected, the error is equal to $\frac{1}{100}$. In general this error is still less except in certain industrial uses. Thus in the laboratory the length heated rarely exceeds 10 cm., and then the error reduces to $\frac{1}{1000}$.

Galvanometers.—The earliest measurements, those of Becquerel and of Pouillet, were made with needle-galvanometers controlled by terrestrial magnetism. These apparatus, sensible to trepidations, require delicate adjustment, and the readings take a long time. The use of these instruments would have prevented the method from becoming practical. It is only thanks to the use of movable-coil galvanometers of the Deprez-d'Arsonval type that the electric pyrometer has been able to become, as it is to-day, an apparatus in current usage.

This apparatus (Fig. 16) is composed of a large horseshoe magnet between whose poles is suspended a movable frame through which the current passes. The metallic wires, which serve at the same time to suspend the coil and bring in the current, undergo then a torsion which is opposed to the displacement of the coil.

The latter stops in a position of equilibrium which

depends both on the strength of current and the value of

FIG. 16.

the torsion couple of the wires. To these two forces is added, in general, a third, due to the weight of the coil, which causes disturbing effects often very troublesome. We shall speak of this further on.
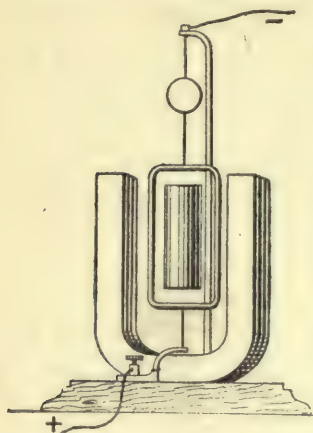
The measurement of the angular displacement of the coil is made sometimes by means of a pointer which swings over a divided scale, more often by means of a mirror which reflects on a semitransparent scale the image of a wire

stretched before a small opening conveniently lighted.

These movable-coil galvanometers were for a long time considered by physicists as unsuited for any quantitative measurements; they were only employed in mill methods and made accordingly. In order to render them suitable for quantitative measurements of current it was necessary to attend to a series of details of construction, previously neglected. Here are the most important among these.

1. The *movable coil* should possess a resistance as little variable as possible with the surrounding temperature in order to avoid corrections always very uncertain. The coils of copper wire ordinarily used to augment the sensibility should be absolutely discarded; use should be made of coils of German silver or of similar metal with small temperature coefficient.

2. The spaces which separate the coils, from the poles of the magnet, on the one hand, and from the central soft-iron core on the other, should be sufficiently great to avoid with certainty any accidental friction which would prevent the free movement of the coil. A width of

2 mm. is convenient; it will hardly do to decrease this. The rubbings to look out for do not come from the direct contact of the frame with the magnet: these latter are too visible to escape unseen. Those which are to be guarded against come from the rubbing of filaments of silk which stand out from insulating covering of the metallic wires, and from the ferruginous dust which clings to the magnet. It is here, it would seem, that the most serious source of error is met with in the use of the movable-coil galvanometer as measuring instrument. There is no warning indication of these slight rubbings which limit the displacement of the coil without, however, taking from it its apparent mobility.

3. The suspending wire should be as strong as may be to support the coil without being exposed to breaking by shocks; on the other hand, it should be very fine, so as not to have too great a torsion-couple. Two different artifices help to reconcile somewhat these two opposed conditions: the use of the mode of suspension of Ayrton and Perry, which consists in replacing the straight wire by a spiral made of a flattened wire, or more simply the use of a straight wire flattened by a passage between rollers.

The first method offers the greatest security from shocks; it is, on the other hand, more difficultly realizable; minute precautions should be taken to prevent any rubbing between adjoining spirals. The second method allows more easily having the large angular displacements which are indispensable when it is desired to take readings upon a dial.

The most essential property necessary for the wires is absence of permanent torsion during the operations. These torsions cause changes of zero which may render worthless all the observations if account is not taken of this, which complicates matters considerably if such cor-

rection has to be made. This result is reached by using wires as long as possible, having not less than 100 mm. length, and by avoiding giving to them an initial torsion, a precaution that should be kept constantly in mind, which it often is not. When one wishes to adjust the coil to the zero of graduation, one turns often haphazard either one of the wires; it may be then that each of the wires is given an initial torsion of considerable magnitude and of opposite sign. If the two wires are not symmetrical, as is ordinarily the case, the permanent deformation resulting from this exaggerated torsion will cause a continual displacement of the zero which may last for weeks and months, increasing or decreasing during the observations according to the sense of displacement of the coil. This torsion is easy to obviate at the time of construction, but it is not possible to verify later its absence in the case of round wires or spirals except by dismounting the apparatus. On the contrary, by the use of stretched flat wires it is very easy upon simple examination to determine the existence or absence of torsion. This is another reason for employing them.

Finally, use must be made of wires having a very high elastic limit. For that it is necessary that the metal has been hardened, and besides that the metal does not undergo spontaneous hardening at ordinary temperatures. Silver, generally employed as suspension wire, is worthless. A metal, as iron, which even after annealing possesses a high elastic limit would be perfect if it were not for its too great alterability. One cannot be sure of having uniform hardening, because the soldering of wires, indispensable to assure good contacts, anneals them throughout a certain length. German silver is the metal the most frequently used in galvanometers destined for pyrometric measurements. The alloy of platinum with 10 per cent of nickel

seems preferable; after annealing it has a high elastic limit, and possesses a tenacity much higher than that of German silver. Its disadvantage is to possess a limit of elasticity twice as great, which reduces by one-half the deflections of a given cross-section of wire.

4. *Installation of the apparatus* for the galvanometers, in which the coil is carried by two opposed *stretched* wires, necessitates special precautions.

In the first place it should be located beyond the influence of trepidations of the ground, which render reading impossible; then it is necessary that its position remain *rigorously* fixed. If, in fact, the two extreme points of suspension of the wires are not exactly in the same vertical, and if the centre of gravity of the coil is not exactly in the line of the two points of suspension, two conditions which can be never rigorously realized, the apparatus constitutes a bifilar pendulum of great sensibility. The slightest jarring suffices to provoke very considerable angular displacements of the coil. To avoid them, the apparatus should rest upon a metallic support attached to a wall of masonry. When the apparatus is placed, as is often the case, upon a wooden table resting upon an ordinary wooden floor, in order to obtain a deflection of the coil, and in consequence a displacement of the zero, it suffices to walk around the table, which causes the floor to bend slightly, or to provoke a current of air, which, in changing the hygrometric state of the legs of the table, causes it to tip somewhat.

Coils freely suspended from above have not these disadvantages.

Different Types of Galvanometer.—A series of galvanometers have been studied especially in view of pyrometric measurements; we will pass them rapidly in review.

For laboratory researches the usual swinging-coil galva-

nometer as made by Carpentier is often used.   One must
make sure that these instruments satisfy well the indispensa-
ble conditions which we have mentioned, which is not always
the case when these instruments have been constructed
with reference to the ordinary experiments of physics.
These conditions are:

Coil of German-silver wire of a resistance of 200 ohms.

Sufficient free space between coil and magnet.

Invariability of zero, even after a considerable deflection
of coil.

Installation on a firm support.

This laboratory apparatus, the only one which existed
at the time of the first investigations of Le Chatelier, was
not transportable and could not be arranged for ex-
periments in industrial works.   It was then necessary
to devise a special model of galvanometer easy to carry
about and to put in place.   The apparatus (Fig. 17) is
composed of two parts, the galvanometer and the trans-
parent scale with its light.   The two parts are symmetrical
and, for transportation, may be fixed back to back on the
same plank carrying a handle.   For observations they are
fastened to a wall by means of two nails driven in at a
suitable distance apart.   The suspension wires, in case of
breakage, may be immediately replaced.   They carry,
soldered to their two ends, small nickel spheres, which one
has only to slip on to forked pieces attached to the top and
bottom of the coil, and to the supports of the apparatus,
respectively.   The mirror consists of a plano-convex lens,
silvered on the plane face, which gives much sharper and
brighter images than the ordinary small mirrors with
parallel faces.

Lately, Carpentier has made for the same purpose a
galvanometer in which the readings are taken by means of
a microscope.   It is an easily transportable apparatus and

very convenient. It has only the fault to be subject to a displacement of the zero resulting from the unsymmetrical heating of the body of the microscope by the small lamp
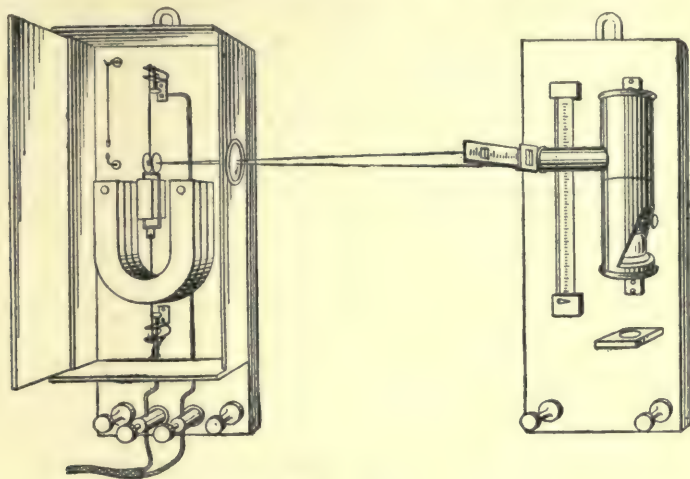
FIG. 17.

which lights the reticule. The stretched wires are replaced by large spirals which offer an absolute resistance to rupture by shock during transportation.

The use of this apparatus necessitates an arrangement which permits, during the observations, putting the galvanometer on open circuit so as to verify the zero reading.

In the three preceding galvanometers the measurement of the deflection of the coil is made by optical means; in the three following, the measurement is made by means of a needle swinging over a scale.

After a study made by Holborn and Wien at the Physikalische Reichsanstalt in Berlin of the Le Chatelier thermoelectric pyrometer, the firm of Kayser and Schmidt devised a needle-galvanometer (Fig. 18) which works fairly well. It has the disadvantage of being somewhat fragile. The suspending wire of the coil does not seem to have more than $\frac{1}{20}$ mm. diameter; the mounting of the

apparatus is quite complicated. Repairs cannot readily
be made either in the laboratory or works.
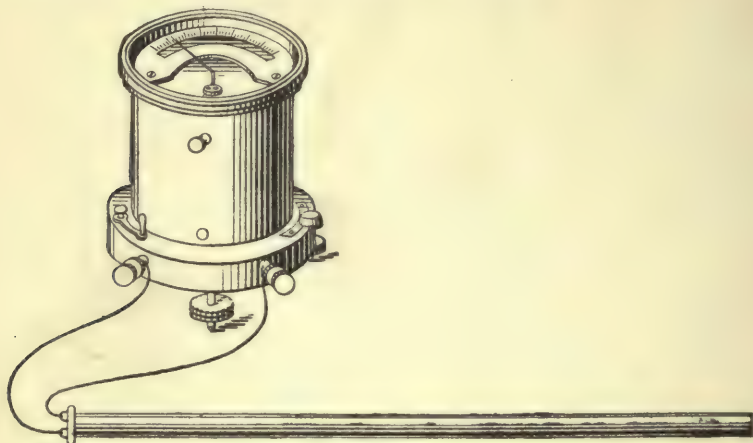
Fig. 18.

The firm Siemens and Halske, which has commenced
recently to build Deprez-d'Arsonval galvanometers, has
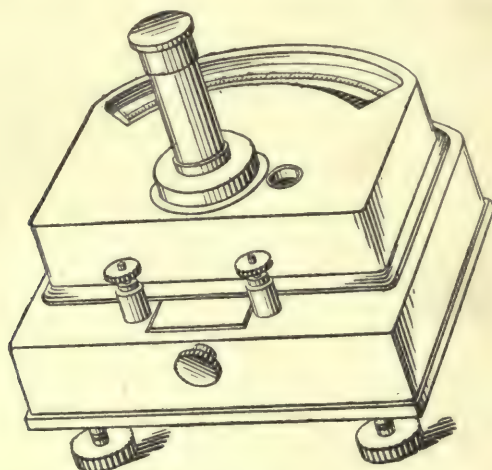
Fig. 19.

also devised a model of needle-galvanometer fitted for
temperature measurements (Fig. 19). Its resistance is
340 ohms; the scale has 180 divisions, each corresponding

to 10 microvolts. There is also a second graduation which gives the temperature directly with the couple sold with the apparatus. Commutators allow of putting the apparatus successively in communication with different thermo-electric couples, if it is desired to take simultaneously several sets of observations.

Pellin, of Paris, has made, from designs of Le Chatelier, a needle-galvanometer (Fig. 20) of simple construction
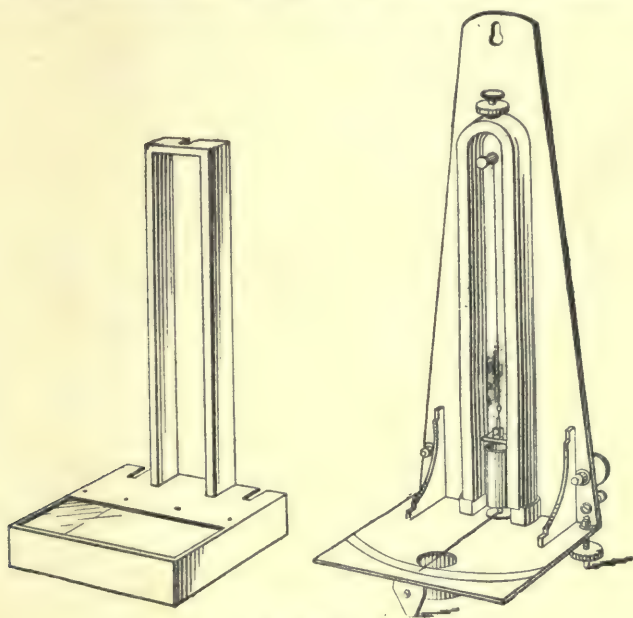
FIG. 20.

which can be repaired where it stands. The very long suspension wire is of 10 per cent nickel-platinum; it has $\frac{1}{10}$ mm. diameter and is drawn out flat.

The lower wire is made of a spiral of the same wire of $\frac{1}{20}$ mm. diameter, which is situated in the interior of the iron core so as to insure uniformity of temperature. When the spirals of the suspension are unequally heated by radiation from the room or for other reason, there results considerable displacement of the zero. A spirit-

level permits of rendering the apparatus vertical, but it is prudent, by reason of the length of the suspension wire, to make sure directly of the absence of rubbing on the coil. For this a slight jar is given to the apparatus; the point of the needle should take up and keep for a long time a slow oscillatory movement in the direction of its length; the transverse oscillations ceasing rapidly indicate friction upon the coil. Evidently use may be made of a great number of other models of galvanometer which are to be found on the market; but on the condition to make sure in the first place that they satisfy the conditions necessary for good temperature measurement, which is rarely the case.

Arrangement of the Wires of the Couple.—For good working of the couple there are certain practical precautions to be taken, which we shall consider.

Junction of the Wires.—The contacts of the different parts of the circuit should be assured in a positive manner; the best way is to *solder* them. Binding-screws often work loose in time, or the metallic surfaces in contact become oxidized. The importance of this precaution varies with the conditions of the experiments; one can dispense with it for experiments that last only a few hours, because there is little chance that the contacts become modified in so short a time; soldering is on the contrary indispensable in an industrial installation which will have to be used for months without being tested anew.

But in any case the soldering together of the two leads of the couple is absolutely indispensable. It is quite true that the electromotive force is independent of the manner of making contact. The two wires twisted together or soldered will give at the same temperature the same electromotive force. But under the action of heat the twisted parts are soon loosened, and there result bad contacts

which increase the resistance of the whole circuit. In general this accident is not noticed until the untying is almost complete, so that one may make before this a whole series of false measurements without being warned.

The best method of soldering is the autogène junction by direct fusion of the wires of the couple; it is necessary, in order to effect this, to have oxygen at hand. One commences by twisting the two leads together for a length of about 5 mm., and they are then clamped above an oxy-hydrogen blast-lamp. Oxygen is admitted through the central tube, and gas through the annular space; the oxygen is allowed to flow in normal quantity, and the gas in feeble quantity, then one opens progressively the gas-cock. At a certain instant one sees the extremities of the wires melt, giving off sparks; the gas is then shut off. If one waits too long, the junction will melt completely and the two wires separate.

In default of oxygen, the wires may be soldered with palladium, which can be melted by means of a blast-lamp furnished with air, taking care to reduce the action of radiation. A hole is cut in a piece of charcoal in which is placed the junction of the two wires twisted together after having wound about it a wire or a small strip of palladium, and the flame of the lamp is then directed upon the junction.

In the cases in which the couple is not to be used above 1000°, and only in these cases, the soldering may be done still more simply by the use of gold; the ordinary Bunsen flame is sufficient to make this junction.

Insulation and Protection of the Couple.—The two leads should be, throughout their length, insulated from one another. For this, use is made in the laboratory of glass tubes or pipe-stems, or better still of an asbestos thread wound about the two wires, by crossing it each time

between the two (Fig. 24) so as to make a double knot in the form of an eight, each of the wires passing through one of the parts of the eight. This is by far the most convenient method of insulation for laboratory use. The two wires with their envelope form a small rod of considerable rigidity which is easily slipped into apparatus. With this arrangement it is impossible to go above 1200° or 1300°, at which temperature asbestos melts.

For industrial installations it is better to make use of small fire-clay cylinders of 100 mm. in length and 10 mm. in diameter, pierced in the direction of the axis by two holes of 1 mm. diameter, through which pass the wires. One or another of the other forms of insulator is added in sufficient numbers. They are placed, according to the case, in an iron tube or in a porcelain tube. The porcelain tube should be employed in fixed installations in which the temperatures may exceed 800°. One may, as does Parvillée in his porcelain furnaces (Fig. 21), place the porcelain tube in the lining of the furnace in such a way that its end is flush with the inner surface of the lining. An open space of a decimeter cube is cut in the lining about this extremity of the tube. This method makes easier the establishment of temperature equilibrium without subjecting the tube to too great chances of breaking by accidental blows.

The iron tube is used for temperatures not exceeding 800°, in the lead baths serving to temper steel for example, and for movable couples which are exposed to heat only during the time necessary to take the observations. In this case the junction is placed some 5 cm. beyond the insulators and the iron jacket. The wires take up the temperature within 5 seconds, and the observation can be taken before the tube becomes hot enough to be burned, even in furnaces for steel whose temperatures exceed 1600°, and

before the wires have had time to be altered, even in strong reducing flames. The other extremity of the iron tube carries a wooden handle (Fig. 22) where are located, outside, the binding-posts for the galvanometer leads, and
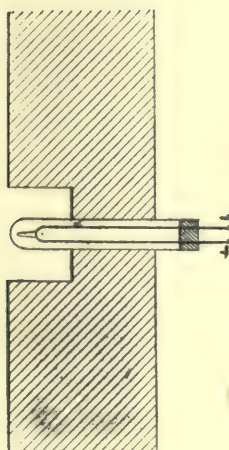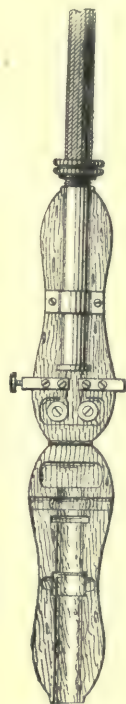

FIG. 21.   FIG. 22.

inside an extra length of wire for the couple to replace portions burned or broken off. The above design gives the arrangement of this handle.

In all cases in which the furnace whose temperature it is desired to measure is under a reduced pressure, suitable precautions must be taken to prevent any permanent entrance of cold air by the orifice necessary for the introduction of the tube, as well before as during an observation. Otherwise one runs the chance of having inexact results.

In the case of prolonged observations in a reducing

atmosphere or in contact with melted bodies, as the metals capable of altering the platinum, the couple should be protected by enclosing it in a covering impermeable to the melted metals and to vapors. For fixed installations in industrial works use should be made of a porcelain tube, or one of iron, closed at the extremity where the junction is located; in this case the dimensions of the tube are unimportant. For laboratory investigations it is indispensable, on the contrary, to have around the wires a covering of as small diameter as possible. If it is simply a question of protecting the couple against the action of non-volatile metals, the simplest way is to use, as does Robert Austin, a paste sold in England under the name of Purimachos, which serves to repair the cazettes employed in moulding. We have made an analysis of this which gave the following composition after desiccation at 200°:

Alumina and iron........................ 4
Soda 3.2
Water.................................. 2.6
Silica (by difference) 80.2

It is a very finely powdered quartz to which is added 10 per cent of clay, and diluted with a solution of silicate of sodium. To use it the matter is diluted so as to form a thick paste, and the couple is dipped in it the required length, arranging the wires parallel to each other at a distance apart of about 1 mm.

The whole may then be dried and calcined very rapidly, without fear of snapping the covering, as would happen with clay alone; but this covering is not sufficiently impermeable to protect the couple against the very volatile metals, as zinc. It is better, in this case, to use small porcelain tubes of 5 mm. inside diameter, 1 mm. thickness of wall, and 100 mm. long, straight or curved according to the usage to which they are to be put.

The couple insulated by asbestos thread, as has been said previously, is pushed down to the bottom of the tube. If one has not at hand such tubes of porcelain, and it is required to make a single observation at a temperature not exceeding 1000°, as, for instance, a standardization in boiling zinc, one may use a glass tube. It melts and sticks to the asbestos which holds a thick enough layer to itself to protect the platinum. But on cooling, the tube breaks and it is necessary to make a new set-up for each operation. This is not practicable for continuous observations.

Cold Junction.—In general, in a thermoelectric element, one distinguishes the hot junction and the cold junction. The latter is supposed kept at a constant temperature. In order to realize rigorously this arrangement, three wires are necessary, two of platinum and one of an alloy connecting two junctions. This theoretical arrangement is practically without interest, and the second junction is always dispensed with. If, in fact, the temperature of the whole circuit exclusive of the hot junction is uniform, the presence or the absence of the cold junction does not affect the electromotive force; if this temperature is not uniform, the second junction is not advantageous, for there is then in the circuit an infinity of other junctions just as important to consider: the junctions of the copper leads with the platinum wires, those of the galvanometer leads and of the different parts of the galvanometer among themselves.

One must satisfy himself as well as may be as to the uniformity of temperature in the cold circuit, and rigorously of the equality of temperature between corresponding junctions, particularly those of the two platinum wires with the copper leads. These uncertainties in the temperature of the cold junctions are an important source of error in the measurement of temperatures by thermoelectric

couples. In order to realize measurements precise to 1°, for instance, it will be necessary to have completely homogeneous circuits, including the galvanometer, with the single exception of the junctions of the platinum wires with the conducting leads; these should be immersed in the same bath at constant temperature. It would be necessary for this that the constructors of galvanometers limit themselves to the use of the same German silver for all parts of the apparatus, wires of the coil, suspending wires, leads, and parts of the coil. That is difficult to obtain.

Graduation.—There exist no two couples possessing exactly the same electromotive force. If it were necessary each time to make a comparison with the air-thermometer, this obligation would render illusory the advantages of the thermoelectric method. Practically one is satisfied to make this comparison by means of certain fixed points of fusion and ebullition. But how many must be taken? That depends on the nature of the function connecting the electromotive force and the temperature.

Formula.—Avenarius and Tait have shown that up to 300° the electromotive force of a great number of couples was represented in a manner sufficiently exact by means of a parabolic formula of two terms:

$$e = a(t - t_0) + b(t^2 - t_0^2).$$

The experiments of Le Chatelier on the platinum-palladium couple have shown that the same formula holds also for this couple up to the fusing-point of palladium.

$$e = 4.3t + \frac{7.3}{1000}t^2.$$

$t = 100$	445	954	1,060	1,550
$e = 500$	2,950	10,900	12,260	24,030

But this law fails completely for couples made of pure platinum and an alloy of this metal. Here are three series of determinations made with different couples:

Barus. Pt—Pt 10% Ir.		Le Chatelier. Pt—Pt 10% Rh.		Holborn and Wien. Pt—Pt 10% Rh.	
t	e	t	e	t	e
300	2,800	100	550	100	565
500	5,250	357	2,770	200	1,260
700	7,900	445	3,630	400	3,030
900	10,050	665	6,180	600	4,920
1100	13,800	1060	10,560	800	6,970
		1550	16,100	1000	9,080
		1780	18,200	1200	11,460
				1400	13,860
				1600	16,220

Holman has shown that the results of Holborn and Wien could be expressed by a logarithmic formula containing only two parameters. All such observations may be represented by a similar formula. Those of Le Chatelier satisfy

$$\log e = 1.2196 \log t + 0.302;$$

e is expressed in microvolts.

The following table (p. 120) gives a comparison of the results observed with those calculated by means of the preceding formula:

The same formula has been applied successfully to the observations of Barus on platinum-iridium couples.

Fixed Points.—This formula includes only two parameters which may be determined by means of two observations. It will suffice therefore to have two fixed points to graduate a couple, on the condition, however, that they be taken far enough apart. It will be well to choose them in the neighborhood of the region of temperatures in which the couple is to be especially employed. If two

t (observed)	t (comp.)	e (in microvolts)	$\log e$	$\log e - 0.3020$	$\text{Log } t = \dfrac{\log e - 0.3020}{1.2196}$
100°	102°.5	565	2.7520	2.4500	2.010
$\varDelta =$	(+2.5)				
200	198.2	1,260	3.1004	2.7984	2.297
	(−1.8)				
400	405	3,030	3.4814	3.1794	2.608
	(+5)				
600	602	4,920	3.6920	3.3900	2.780
	(+2)				
800	800	6,970	3.8432	3.5412	2.903
	(0)				
1000	996	9,080	3.9581	3.6561	2.998
	(−4)				
1200	1208	11,460	4.0591	3.7571	3.082
	(+8)				
1400	1410	13,860	4.1418	3.8398	3.150
	(+10)				
1600	1603	16,220	4.2100	3.9080	3.205
	(+3)				

observations are sufficient theoretically, it will be prudent in practice to utilize for the graduation a greater number of fixed points so as to have a check on the accuracy of the observations. The points whose use is to be recommended by reason of the accuracy with which they are known, and for their ease of use, are the following:

Ebullition of water;

Ebullition of naphthaline or, in default, the fusion of tin;

Ebullition of sulphur or, in default, the fusion of zinc;

Ebullition of zinc or, in default, the fusion of gold;

Fusion of platinum.

The fusing-points are easier to use than the boiling-points at high temperatures; but their precision is slightly less.

For the *boiling-points* of water, naphthaline, and sulphur it is convenient to make use of an arrangement due to Barus (Fig. 23). This consists of a tube of thin glass, similar to test-tubes, of 15 mm. inside diameter, 300 mm. long, with a small bulb at 50 mm. below the open end. It is surrounded with a plaster muff of 150 mm. height and 100 mm. diameter which has been cast about the glass tube inside of a thin metallic cylinder forming the outside surface. The bulb is immediately above the plaster jacket, below which the tube, closed at its lower end, extends to a distance of 70 mm. As soon as the plaster has begun to set, the glass tube is taken out, giving it a slight twisting motion. The cylinder is left to dry, and the tube is again put in place.
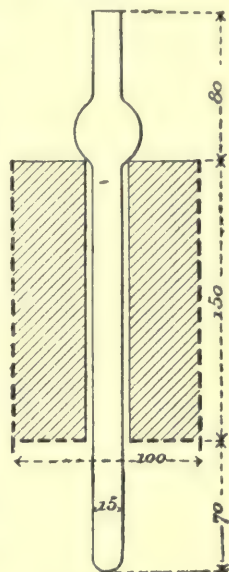
FIG. 23.

This allows, when the tube is broken, to take it out and replace it, which would be difficult if it adhered to the plaster.

The lower free portion is heated by a Bunsen flame, gently at first, then without any special precaution, once boiling sets in. The liquid at rest should occupy two-thirds of the height of the free end of the tube. The heating is continued until the liquid coming from the condensation of the vapor runs abundantly down the walls of the bulb. The flame is then adjusted so that the limit of condensation of the liquid, which is very sharp, remains constantly midway up the bulb. There is then a perfectly uniform temperature in the interior of the glass tube throughout the height of the plaster cylinder. The junc-

tion of the couple is inserted and the coil of the gal-
vanometer takes up a fixed invariable position.*

For the boiling-point of zinc Barus made small cruci-
bles of porcelain very ingeniously arranged, but also very
complicated, besides being fragile and costly.   One can
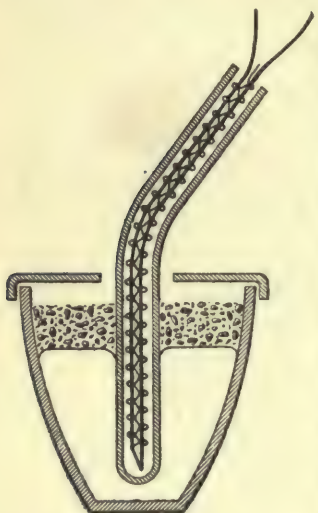make use more simply of a porcelain crucible 70 mm.

deep (Fig. 24), filled with melted
zinc for 50 mm. of its depth, and
above, 20 mm. of charcoal-dust.
A cone pierced with a central hole
lets pass a small porcelain tube
containing the couple.   The whole
is heated until there is seen a small
white flame of zinc escaping from
the crucible.   It is indispensable
that the openings for the escape
of zinc vapor be large enough.
They tend, indeed, to become
clogged by a deposit of zinc oxide
which solders at the same time the
cover to the crucible, and this

Fig. 24.

causes an explosion when there is no longer vent for the
zinc vapors.

Use may be made to advantage for this heating, and still
more for the heating of small crucibles to a very high tem-
perature, of a furnace model of English make (Fig. 25),
which has the advantage to resist almost indefinitely the
action of heat and to be very easily repaired.   The princi-
ple of the construction of these furnaces is to make them
of two concentric layers.   The outer covering of fire-clay,
bound together by iron, gives solidity to the furnace; it

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* It is well to prevent the liquid from running down about the
couple by placing a small cone of platinum above the junction.—Tr.

receives but indirectly the action of the heat, and is not exposed to cracking by shrinkage under the action of too high temperatures. The inner envelope, which alone receives the action of the heat, is made of large-grained quartz sand, grains of 1 mm., mixed with a small amount of a flux. At a high temperature the quartz does not shrink as does clay; it expands, on the contrary, passing over to the form of amorphous silica with a change of density from 2.6 to 2.2. But this transformation is effected only with extreme slowness, otherwise it would burst the furnace. If by chance this inner lining falls down, it is easily replaced by putting into the furnace a glass jar of
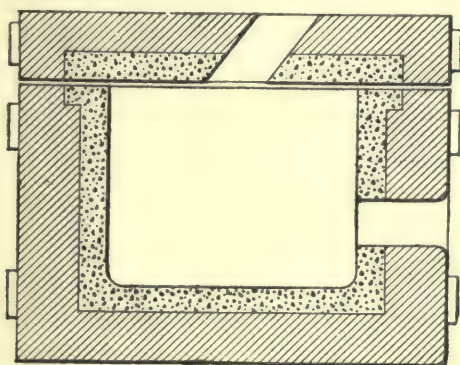
FIG. 25.

suitable diameter, surrounded with a sheet of oiled paper, and packing about this, coarse quartz sand slightly moistened with a sirupy solution of alkaline silicate. The furnace is heated by means of a lateral opening with a Fletcher lamp, which has the advantage of being sturdy, or with an ordinary blast-lamp.

In the use of *fusing-points* there are several cases to distinguish. If one wishes to employ a considerable quantity of metal, as with zinc, lead, and tin, the easiest way is to melt them in a crucible, into which is thrust the

properly protected couple and let the whole cool. There is observed with no difficulty the stationary temperature of solidification.

If only a small quantity of metal can be employed, as in the case of gold, or if there is no installation for heating the crucibles, it is possible to obtain the fusing-points as follows: One wraps about the junction, so as to cover it completely, a fine wire of the metal chosen (it suffices with a little practice to use but a centigramme of metal), and then places the couple in an enclosure at stationary temperature slightly higher than that of fusion, or at temperature increasing very regularly. The galvanometer readings are noted, which at the instant of fusion show a momentary halt followed by a sudden jump. But this perturbation is the more feeble the smaller the metallic mass, and a certain practice is necessary in this kind of observation in order to seize with certainty the halting-point. It is evident that the heating must be absolutely regular. It is impossible to obtain this result with a free flame, which is always unsteady. In order to have a stationary temperature, use is made in the laboratory of a tube or a muffle placed in a furnace that has been lighted for some time; at industrial works, a chimney or flue for the escape of smoke. In these enclosures the temperature varies from spot to spot, and one can, after a few trials, find the proper temperature. In order to work at increasing temperatures, which is the most convenient in the laboratory, the junction is placed, properly prepared, in a little crucible filled with powdered, non-fusible, poor conducting material, or else the junction is simply wrapped in a bullet of plaster, clay, or Purimachos. Care is taken to begin by drying and dehydrating slowly this bullet to prevent its bursting. It is then placed in a flame sufficiently hot to bring about fusion of the metal; this flame should be very steady.

For the fusion of platinum a different process should be followed. One utilizes the fusion of the wires of the couple in the same operation which serves to make the junction. Two observers are necessary, one to read the galvanometer and the other to note the fusion of the platinum. It is necessary to employ a flame sufficiently tall so that the temperature be regular throughout a con-
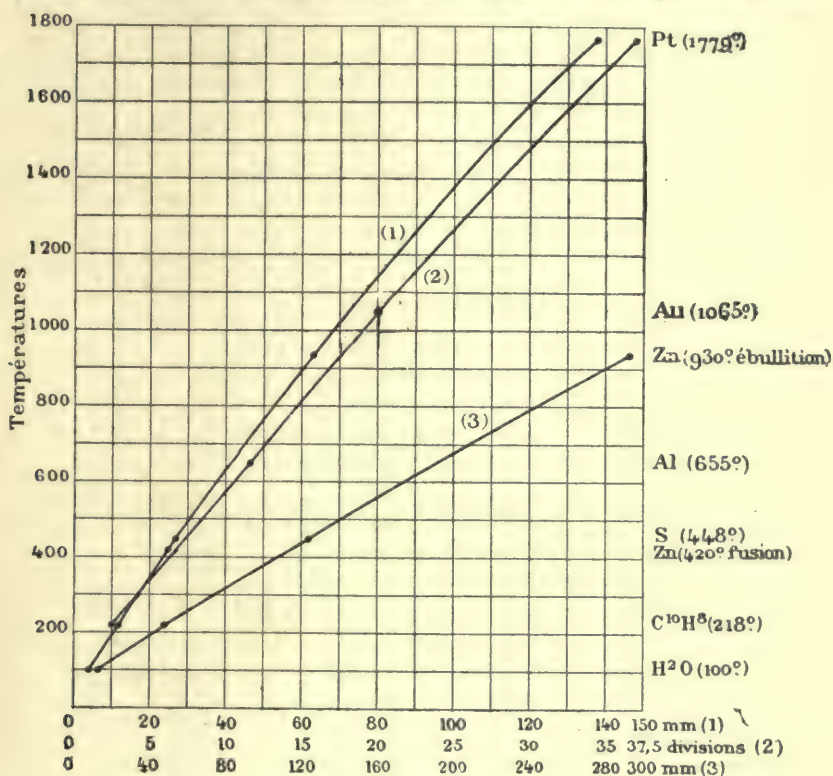

FIG. 26.

siderable height. The junction of the two twisted wires is placed at a distance of at least 50 mm. above the blast-lamp nozzle, a strong blast of oxygen is turned on, and the gas-cock is opened gradually until fusion takes place. The same process should be used for the fusion of gold, with an air blast-lamp, on the condition that the flame of

the latter be kept steady, which is not possible with bellows worked by foot. This method is, however, less precise than those that have been previously indicated.

We give here the curves of graduation (Fig. 26) of different couples, attached to different galvanometers or, in the case of the method of opposition (Poggendorf's method), to a Pouillet rheostat. In the last case the zero of graduation does not correspond to a zero electromotive force, and in consequence not to the temperature of the surrounding air, by reason of the supplementary resistance of a wire which was added to that of the rheostat.

	Fixed Points.	Mirror Galvanometer.	Pointer Galvanometer.	Method of Opposition.
Boiling water......	100°	4.5 divs.		
Boiling naphthaline	218	12 "	2.5 divs.	13 mm.
Melting zinc.......	420	26 "		
Boiling sulphur....	445	28 "	....	123 "
Melting aluminium.	655	....	12 divs.	
Boiling zinc........	930	64	....	294 "
Melting gold.......	1065	....	20 divs.	
Melting platinum...	1780	137.5 divs.	37 "	

Experimental Results.—The measurement of temperatures by thermoelectric couples has enhanced the accurate knowledge of a great number of high temperatures of which previously little or nothing was known. The measurements have been particularly numerous in the scientific and industrial investigations on iron. It is with the thermoelectric couple that Osmond and others, Robert Austin, Arnold, Howe, and Charpy have made all their studies on the molecular transformations of irons and steels. The conditions of manufacture and of treatment of these metals have been improved by the introduction into industrial works of this method of high-temperature measurements.

We give below, as examples, a series of determinations

made by Le Chatelier in a certain number of industrial appliances.

Steel.—Siemens-Martin furnace:

Gas at the outlet of the gas-generator.................	720°
Gas at the entrance of the recuperator..............	400
Gas at the outlet of the recuperator.................	1200
Air " " " " " "	1000
Interior of the furnace during refining..............	1550
Smoke at the foot of the chimney....................	300

Glass.—Basin furnace for bottles; pot furnace for window-glass:

Furnace...	1400°
Glass in affinage..................................	1310
Annealing of bottles...............................	585
Drying of window-glass............................	600

Illuminating-gas.—Gazogène furnace:

Top of furnace....................................	1190°
Base of furnace...................................	1060
Retort at end of distillation.......................	975
Smoke at base of recuperator......................	680

Porcelain.—Furnaces:

Hard porcelain....................................	1400°
China porcelain...................................	1275

Conditions of Use.—Thermoelectric couples by reason of their easy use and of the precision of their indications are preferable to all other pyrometric methods for ordinary investigations, scientific or industrial, and in fact they are almost the only ones employed to-day for such uses. Their employment, however, is not to be recommended for investigations of the highest precision; the preference should be given, as we have already said, to the electric-

resistance pyrometer * as soon as we possess the means to graduate it with precision up to high temperatures. From another standpoint one will be led to discard the thermo-electric couples when one does not possess a sufficiently skilful personnel to make the necessary small electric installation, or when one shrinks from the expense of buying a galvanometer.

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* But see recent work at the Reichsanstalt on this point, especially regarding the evaporation of platinum at high temperatures.—TR.

CHAPTER VII.

HEAT-RADIATION PYROMETER.

Principle.—The quantity of heat that a body receives by radiation from another body depends on certain conditions relative to each of the two bodies, which are:
1. Temperature;
2. Surface;
3. Distance apart;
4. Emissive and absorbing power.

In order to utilize heat radiation for the determination of temperatures, one measures a heat change produced on the body used as instrument by the body to be studied; this heat change is either a rise of temperature or a resulting phenomenon, such as a change of electrical resistance, thermoelectromotive force, etc.

The quantity of heat given off is proportional to the radiating surface S, and varies inversely as the square of the distance l.

$$q = k\frac{S}{l^2} = k'\frac{d^2}{l^2} = k''E \cdot \frac{d^2}{l^2},$$

d being the diameter of the radiating surface S, E its emissive power.

Now, $\frac{d}{l}$ is the apparent diameter of the object; the quantity of heat radiated depends then upon the solid angle under which the object is seen.

The emissive power E is very variable from one substance to another, and for the same substance variable with the

temperature. It would be desirable to determine this, but that is difficult, often impossible, especially at high temperatures.

The coefficient k'' is a function of the temperature alone, which expresses the law of variation of the radiation with the temperature. This law should be determined in the first place. It is on the more or less exact knowledge of this law that the entire accuracy of the results depends. The precision of the experimental measurements has not practically, as things are, other than a secondary importance.

Let us see now what are the experimental arrangements which have been used to measure the intensity of heat radiation; these measurements have had for their only aim, until now, the determination of the sun's temperature, but they may serve other uses.

Pouillet's Experiments. — Before Pouillet, Gasparin had already made some trials. His apparatus consisted of a hollow brass sphere mounted on a foot and blackened; a thermometer was used to measure the rise in temperature of the water contained in the sphere. The advantage of this arrangement was that the apparatus was always turned properly toward the sun.

The *pyrrhéliomètre* of Pouillet consists of a calorimeter which measures directly the heat received by radiation (Fig. 27). A very thin silver box is carried by a hollow tube, cut along a generatrix to let the thermometer be seen.

FIG. 27.

The box is of 100 mm. diameter by 15 mm. height; it contains 100 cc. of water. At the lower part of the box is located a metallic disk of the same diameter as the box, and meant to turn the apparatus toward the sun; it suffices, in fact, for the shadows of the box and disk to coincide exactly in order that the system be properly pointed. A knob serves to turn the apparatus about its axis in order to stir the water. Finally a support gives the means of placing the system in any desired orientation.

To take an observation, the apparatus is set up and shielded from the sun's action by means of a screen; the readings of the thermometer are taken for five minutes; the screen is removed and the thermometer is read for five minutes; the screen is put back, and a new set of readings of the thermometer for five minutes is taken.

The first and the third sets furnish the corrections due to the surroundings. Pouillet observed in this way a rise of temperature of 1° in five minutes.

In the determination of the temperature of the sun it was evidently necessary to take into account the heat absorbed by the atmosphere (it is about 20 per cent of the total radiation from the sun). Pouillet found by this method 1300° for the temperature of the sun.

Experiments of Violle.—Violle makes use of an *actinomètre,* whose principle is quite different from that of the preceding apparatus; one observes the stationary equilibrium of a thermometer receiving simultaneously radiation from an enclosure at fixed temperature, and that from the hot substance to be investigated (Fig. 28).

The apparatus consists of two spherical concentric coverings of brass, in which a water circulation may be set up at constant temperature, or ice may be substituted for water. The inner covering of 150 mm. diameter is blackened inside. The thermometer has a spherical

bulb whose diameter varies from 5 to 15 mm.; the surface of the bulb is also blackened. The scale is divided into fifths of a degree. The entrance-tube carries a diaphragm pierced with holes of different diameter; on the extension of this tube is located an opening closed by a ground-glass
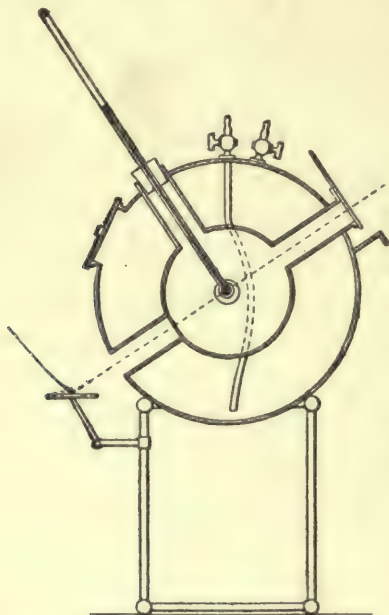

Fig. 28.

mirror slightly blackened, which permits of determining that the solar rays fall quite exactly upon the thermometer bulb.

The establishment of the temperature equilibrium requires fifteen minutes, and the differences of temperature observed vary from 15° to 20°.

Violle found in this way, for the temperature of the sun, figures varying from 1500° to 2500°.

Pouillet and Violle made use of Dulong and Petit's law of radiation,

$$q = a^t,$$

that the discoverers had established by observations reaching 300°.

The constant a may be determined for each apparatus by a single experiment made at a known temperature. This law, as we shall show farther on, is not exact, so that, according to the temperature used to determine the constant, a different value of the latter is found, and consequently also different values at temperatures calculated, assuming this law to hold. This is the reason for the differences between the three figures, 1300, 1500, and 2500, of Pouillet and Violle. They correspond to determinations of the constant obtained by means of preliminary experiments made at the temperatures of 100°, 300°, and 1500°.

The elder Secchi, making use of Newton's formula,

$$q = a(t_1 - t_0),$$

still more inexact, found for the sun's temperature several millions of degrees.

Work of Rosetti.—An Italian savant, Rosetti, was the first to grasp the fundamental importance of the choice of the law assumed for radiating power; he showed that a graduation made by an experiment at 300° gave for the temperature of a body heated in the oxyhydrogen flame:

46,000 if one uses the law of Newton;

1,100 " " " " " " Dulong and Petit.

Now the temperature of the oxyhydrogen flame is about 2000°.

This physicist used a thermoelectric pile whose sensibility could be changed without touching the element; in the apparatus of Violle it is necessary, on the contrary, to change the thermometer, a proceeding which renders the observations comparable with difficulty.

The pile (Fig. 29) consists of twenty-five sheets of

bismuth and antimony; these sheets are very thin, for the whole of the apparatus is but 5 mm. on a side. The whole is enclosed in a small metallic tube.
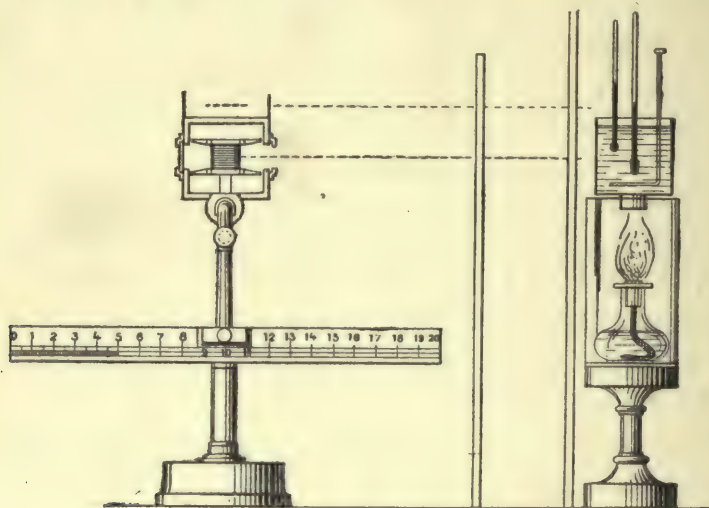
To make an experiment there is placed before the pile a screen filled with water, which is removed at the instant of taking an observation.

A preliminary calibration made with a Leslie's cube of iron filled with mercury that is heated from 0° to 300° gave the following results:

Excess of the Temperature of the Cube over the Surrounding Temperature.	Reading of Galvanometer.
32°.8	10°.
112 .8	55
192 .8	141.9
272 .8	283.5

Newton's law and that of Dulong and Petit giving no concordance between the numbers observed and those computed, Rosetti proposed the formula

$$Q = aT^2(T - \vartheta) - b(T - \vartheta),$$

where T = absolute temperature of the radiating body; ϑ = the absolute temperature of the surroundings. This formula with two parameters permits necessarily a closer following of the phenomenon than a formula with but a single parameter.

$T - \vartheta$	Deflections. Observed.	Deflections Computed. Dulong's Law.	Rosetti's Law.
50	$A = 17.2$	$A + 2.12$	$A - 0.23$
100	46.4	$+ 0.95$	
150	90.1	$- 2.12$	$+ 0.70$
200	151.7	$+ 4.82$	$+ 0.99$
250	234.7	$+ 2.83$	$- 0.12$

Rosetti showed later that the formula he proposed did not lead to absurd results for higher temperatures. A mass of copper was heated to redness in a flame, and the temperature was estimated by the calorimetric method (a quite uncertain method, as the variation of the specific heat of copper is not known). The two methods gave respectively 735° and 760°. This difference of 25° is less than the experimental uncertainties.

Disks of blackened metal placed in the upper part of a Bunsen flame gave, according to the formula, temperatures of the order of 1000°; oxychloride of magnesium in the oxyhydrogen blast-lamp gave 2300°. All these numbers are possible.

Rosetti, using this formula, found 10,000° for the temperature of the sun, this figure resulting from an extrapolation above 300°.

Experiments of Wilson and Gray.—These savants measured the intensity of radiation by means of a thermoelectric couple, a method first conceived by Deprez and d'Arsonval. A movable coil made of two different metals (silver and palladium) is suspended by a silk cocoon fibre between the poles of a magnet. The solar radiation is allowed to fall upon one of the junctions, while upon the other junction

is directed a source of heat which exactly balances the first. As the temperature of this auxiliary source is necessarily the lesser, it is necessary that the apparent angle which it subtends at the galvanometer be the greater.

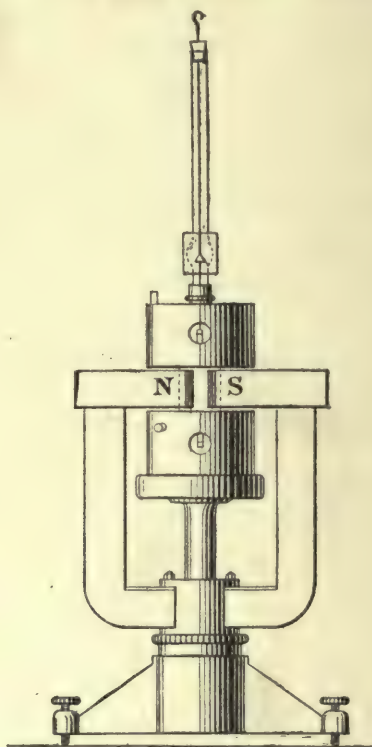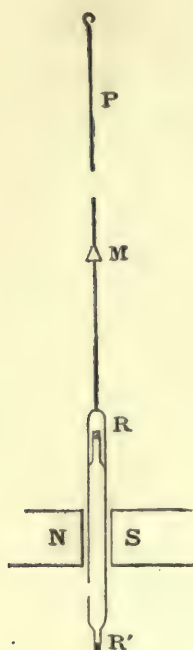Wilson and Gray used an apparatus similar to the radiomicrometer of Boys. The suspending fibre is of

FIG. 30.　　　　　　　　　　FIG. 31.

quartz; the metals employed are bismuth and antimony: the electromotive force so produced is twenty times greater than that obtained with the palladium-silver couple. The metallic strips R and R' (Fig. 30) are very thin (0.1 mm.), which renders the construction of the apparatus quite delicate. In order to protect the movable coil against air-currents, it is enclosed in a metallic case (Fig. 31); an open

tube lets pass in the radiation; diaphragms set inside this tube prevent air-disturbances.

Instead of measuring, as may be done, the deflection of the mobile parts, the investigators preferred to employ a null method making use of another radiation, that from the *meldometer* of Jolly, an apparatus used also for the graduation of the radiomicrometer. The meldometer consists of a strip of platinum heated by an electric current; the dimensions are as follows: 102 mm. in length, 12 mm. in breadth, and 0.01 mm. thick. This strip is placed in the midst of an enclosure surrounded by water. Fastened at one end, it is held in place at the other end by a spring and carries on this end a lever to which is fixed a mirror arrangement serving to amplify the variations in length of the strip resulting from its heating by the passage of the current more or less intense.

The relation between the change of length and the temperature is determined by means of the fusion of very small fragments ($\frac{1}{10}$ milligramme) of bodies whose fusing-points are known. Wilson and Gray used the following, which for gold and palladium are certainly too low:

$$
\begin{array}{ll}
\text{Silver chloride} \dots\dots\dots\dots\dots\dots\dots & 452° \\
\text{Gold} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots & 1045 \\
\text{Palladium} \dots\dots\dots\dots\dots\dots\dots\dots & 1500
\end{array}
$$

With this apparatus they have verified, up to the fusion of platinum, the law of radiation given by Stefan,

$$ Q = a(T^4 - T_0^{\,4}). $$

For the purpose of graduation, the meldometer is removed to a distance such that its action on the radiomicrometer is always the same, and it is assumed that the intensity varies as the inverse square of the distance. It is besides necessary to know the emissive power of platinum;

Wilson and Gray took as starting-points the results given by previous experiments:

$t°$	Emissive Power.
300°...........	$\frac{1}{5.4}$
600	$\frac{1}{4.2}$
800	$\frac{1}{3.9}$

And by extrapolation they found 1/2.9 at the temperature of 1250°, temperature which balanced the solar radiation, with the somewhat large apparent angle subtended by the meldometer. In admitting, then, with Rosetti and Young a zenith absorption of 30 per cent, the temperature of the sun, supposed to be a black body, was found equal to about 6200°.

This figure must be somewhat low, on account of the errors involved in the fusing-points employed for graduation.

Langley's Experiments.—Langley has devised, under the name of bolometer, a radiometric apparatus which he has never used to measure temperatures, but which may be so used like the preceding, and has the advantage over them of being still more sensitive.

It consists of a Wheatstone bridge made of flat wires extremely thin (0.01 mm.) and very short (a few millimeters at the most). The variations of resistance of one of the arms of the bridge submitted to the radiation are measured. The current passing through the system is capable of raising its temperature 3° or 4°; the excess of heat furnished to one of the arms produces a deflection of the galvanometer.

The system is fixed at the bottom of a tube which may be pointed like a telescope toward the body whose radiation is to be measured; diaphragms fixed at various points

stop interior currents of air. One may also, by aid of a lens, concentrate the radiation upon the wire and amplify very much in this way the effect produced when the apparent angle of the object is small.

The bolometer of Langley has up to the present been used almost exclusively to study the distribution of radiant energy in the solar spectrum, and especially in the infrared.

Conditions of Use.—We have dwelt at length upon the radiation pyrometers which have been used up to the present only for a single purpose, the estimation of the sun's temperature, because it is possible that some day or other their usage may penetrate into industrial works, where they may be of real service. In a certain number of industrial apparatus the temperatures are so high that no substance, not even platinum, can resist for long their action. When it is desired to have apparatus of continuous indications, and at the same time unalterable, it will be necessary to make use of radiation pyrometers.

A tube of fire-clay passing through the lining of the furnace, and penetrating into the midst of the latter for a distance of 0.50 m. to 1.00 m., closed at the inner end and open at the outer, would give a radiating surface at the temperature of the furnace which could be examined by means of a lens projecting upon the measuring apparatus the image of the sealed base of this tube.

CHAPTER VIII.

LUMINOUS RADIATION PYROMETER.

Principle.—Instead of using the totality of the radiant energy as in the methods described in the preceding chapter, use is made of the luminous radiations only. This utilization may be effected in many different ways, which give methods of unequal precision and varying in facility of manipulation.

Before beginning their study, it is well to recall certain properties of radiations.

Kirchoff's Law.—An incandescent body emits radiations of different wave-lengths. For a given wave-length and a given temperature the intensity of this emitted radiation is not the same for different bodies: this is expressed by saying that they have for this radiation different *emissive powers*. Similarly, a body which receives radiations of a given wave-length absorbs a part of them and sends back another part by diffusion or reflection; a certain quantity may also traverse the body. The *diffusing, reflecting*, or *transmitting* power at a given temperature, for a given wave-length, varies from one body to another. The *emissive power and the diffusive power* (in the case of an opaque and non-reflecting body) *vary always inversely, resting complementary to each other.*

Substances of great emissive power, as lampblack, have a small diffusive power; substances of small emissive power, as polished silver, magnesia, have a very great diffusing or reflecting power.

If we take as the measure of the emissive power the

ratio of the intensity of the radiation of the body considered to that of lampblack at the same temperature, and as measure of the diffusive power the ratio of the intensity of the radiation diffused to the incident radiation, the sum of these two quantities is equal to unity.

Kirchoff has shown that in an enclosure at constant temperature, pierced with a small opening so as to enable one to look inside, the intensity of each radiation depends only upon the temperature and is independent of the nature of the substances. Substances of great emissive power, as lampblack, have an intensity of radiation approaching in value that of such an enclosure without ever being superior to it.

For short, we shall call black absorbing body or simply *black body* a body which would have the same emissive power as the enclosure mentioned, and which emissive power will be taken as unity.

The emissive power of a body varies from one radiation to another, and consequently also its diffusing and transmitting powers, since these two powers are complementary to each other. It follows that the relative proportions of the visible radiations received or given off by a body are not the same; so that different bodies, at the same temperature, appear to us to be differently colored.

At the same temperature, the color proper to a body, and its apparent color when it is lighted by white light, are complementary to each other. Yellow substances, as oxide of zinc heated, emit a greenish-blue light. At temperatures less than 2000° the red radiations predominate greatly and mask the inequalities of the radiations of other wave-lengths. To render easily visible the colorations of radiating bodies it is necessary to compare them with those of a black body under the same temperature conditions. A hole pierced in the body, or a crack across

the surface, gives a very good term of comparison to judge of this coloration.

The intensity of the radiations emitted by a black body increases always with the temperature, and the more rapidly as we approach the blue region of the spectrum; but on the other hand the radiations from the red end are the first to commence to have an intensity appreciable to vision, so that the color of bodies heated to higher and higher temperatures starts with red, tending towards white, passing through orange and yellow. White is, in fact, the color proper to bodies extremely hot, as is the sun.

Bodies not black have a law of decrease different from that for black bodies, because the emissive power varies with the temperature. It increases unequally for the various radiations, so that the color of bodies, with respect to the color of a black body, changes with the temperature.

The following table gives for different colors the ratios of the values of emissive powers of some bodies to that of a black body. The red radiation was observed through a glass containing copper, the green by aid of a chromium copper glass, the blue through an ammoniacal solution of cupric hydrate. The substance covered the junction of a thermoelectric couple, and was cut by grooves; and it was the brightness of the bottom of these grooves which was compared to that of the surface.

		R. Red.	R. Green.	R. Blue.
Magnesia.............	at 1300°	0.10	0.15	0.20
	1550	.30	.35	.40
Lime.................	1200	.05	.10	.10
	1700	.60	.40	.60
Oxide of chromium.......	1200	1.00	1.00	1.00
	1700	1.00	.40	.30
Oxide of thorium........	1200	.50	.50	.70
	1760	.60	.50	.35
Oxide of cerium..........	1200	.80	1.00	1.00
	1700	.90	.90	.85
Auer mixture...........	1200	.25	.40	1.00
	1700	.50	.80	1.00

The estimation of temperature, from measurements of radiations, may, at least in theory, be made in three different ways, by utilizing:

The total intensity of the luminous radiation;

The intensity of a radiation of definite wave-length;

The relative intensity of radiations of definite wave-lengths.

Measurement of the Total Intensity of Radiation.—The brightness of substances increases very rapidly with the temperature. One may with the unaided eye estimate comparatively this brightness, but this measurement is very uncertain, for lack of a constant standard of comparison. The sensitiveness of the eye varies, in fact, with the individual, with the light which the eye received immediately preceding, and with the attendant fatigue. Photometric processes, precise for comparison with a standard source, cannot be employed on account of the change of hue with the temperature.

The following method might be tried: trace on a white surface, diffusive or translucent, marks of definite intensity and dimensions, and seek what fraction of the light must be employed to render the marks invisible. The indications will be still quite variable and will depend upon the degree of the eye's fatigue.

We can then say that there actually exists no definite method based on the appreciation of the total intensity of radiation for the estimation of temperatures.

Measurement of the Intensity of a Simple Radiation — We may estimate the temperature of a body from the intensity of one of its radiations, provided that we know the emissive power of the body at that temperature and the law of variation of this radiation determined in terms of the air-thermometer.

The emissive power varies with the temperature, and

generally is not konwn.   It might seem that this would be enough to reject this method and similar methods by radiation.   But this is not so, for the following reasons:

1. At temperatures higher than the fusing-point of platinum there is no other pyrometric method applicable.

2. A great many bodies have a considerable emissive power, nearly unity, and particularly some bodies of industrial importance, as iron and coal.

3. The variation of radiation with temperature is sufficiently marked so that the errors committed in neglecting the emissive power are small.   Thus at 1000° the red radiation emitted by carbon is quadrupled for an interval of 100°; it is doubled at 1500° for the same temperature interval.

Then, except for some bodies exceptionally white, the emissive powers at high temperatures are superior to 0.5. By taking them equal to 0.75, the greatest error that will be made, for the ordinary temperatures comprised between 1000° and 1500°, will be from 25° to 50°.

Optical Pyrometer of Le Chatelier.—Ed. Becquerel had proposed in 1864 to refer the measurement of high temperatures to the measurement of the intensity of red radiations emitted by incandescent bodies; but this method had never been realized in a complete manner, and still less employed.   Le Chatelier, taking up the question, devised an experimental arrangement suitable for such measurements, and he determined the *law of radiation* of substances in terms of the temperature.

Photometer. — For these measurements a photometric apparatus is required which gives, not as do the ordinary photometers, a measurement of the total illumination produced by a source (illumination which varies with the dimensions of this source) but the intrinsic brightness of

each unit of surface.   Use may be made of a photometer based on a principle due to Cornu.

The apparatus (Figs. 32 and 33) consists essentially of a telescope which carries a small comparison-lamp attached laterally.   The image of the flame of this lamp is
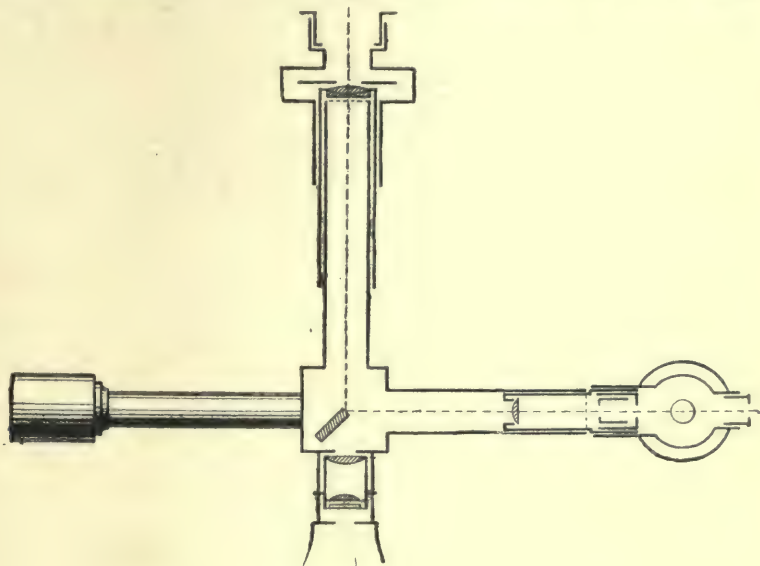

FIG. 32.

projected on a mirror at 45° placed at the principal focus of the telescope.   One adjusts for equality of intensity the images of the object that is viewed and of the comparison-flame, these images being side by side.

The telescope comprises an objective in front of which is placed a cat's-eye diaphragm which admits of varying the effective aperture of this objective, and beyond, a stand destined to carry tinted absorbing-glasses.

At the focus of the objective is a mirror inclined at 45° which reflects the image of the lamp projected by an intermediary lens.   An ocular, before which is placed in a set position a monochromatic glass, serves for observing the images of the flame and of the object.

To the lamp is fixed a rectangular diaphragm which stops the luminous rays not utilized and which carries a stand to receive tinted absorbing-glasses.

The edge of the mirror at 45° is in the plane of the image of the source studied, so that the reflected image and the direct image are side by side, separated only by the
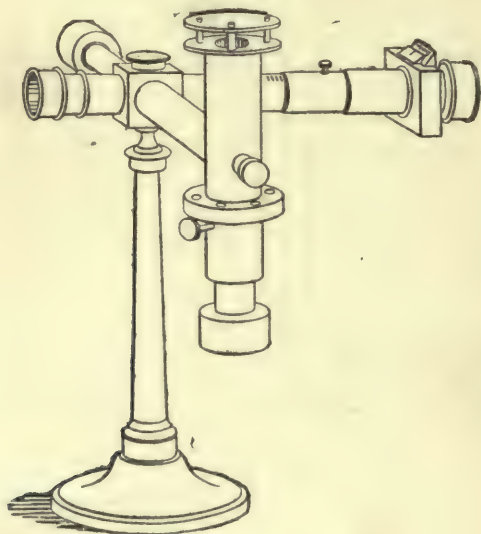
FIG. 33.

edge of the mirror. This mirror, according to a method devised by Cornu, is made of a plate of black glass cut with a diamond, which gives a very sharp edge.

In order to vary the relative intensities of the images, one thus employs simultaneously tinted glasses placed before one or the other of the two objectives, and the cat's-eye mentioned. A screw allows of varying the aperture of this cat's-eye, and a suitable scale indicates the dimensions of this opening.

It is very important that the tinted glasses have an absorbing power as uniform as possible and do not possess absorption-bands. These conditions are fulfilled by

certain smoked glasses of ancient make (CuO, Fe_2O_3, MnO_2); for the fabrication of these glasses use is now made of the oxides of nickel and cobalt, which give absorption-bands.

To determine the absorbing power of these glasses, a measurement is made with and without them; the ratio of the squares of the aperture of the cat's-eye gives the absorbing power.

For monochromatic screens one may use:

1. Red copper glass, which lets pass $\lambda = 659$, about. This one is preferable, as it is more nearly monochromatic and because measurements at low temperatures may be made with it, the first radiations emitted being red.

2. Green glass ($\lambda = 546$, about). The observations are then easier than in the red, but they can be commenced only at higher temperatures.

3. Ammoniacal solution of copper oxide ($\lambda = 460$, about). The use of this last screen, which is far from monochromatic, is without interest; the eye is only slightly sensitive to the blue radiations, and these last become somewhat intense only at high temperatures.

Adjustment of the Apparatus.—There are in the apparatus two parts which require very careful adjustment for best results, and these parts should consequently be so made as to admit of the necessary manipulation to obtain the desired effect.

1. The luminous beam coming from the lamp and which is reflected by the mirror, and that which comes directly from the object viewed, should penetrate into the eye in their totality. This condition is fulfilled if the images of the two objectives given by the ocular are superposed.

This is verified by examining with a lens these two images which are formed slightly behind the collar of the ocular. It is evidently necessary, in order to see them, to

illumine the two objectives, one with the lamp, the other with any source of light. If the superposition does not exist, it is established by trial by turning the screws which hold the mirror. If it is not jarred, the apparatus should remain indefinitely in adjustment.
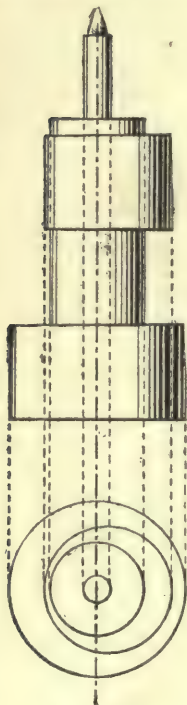
In order that a steady light may be had, certain precautions in the adjustment of the comparison-lamp are necessary. As far as possible, one should always employ the same kerosene. The flame should have a constant height, equal, for example, to the window of the rectangular diaphragm placed before the flame. Its image should be cut exactly in two by the edge of the mirror, a result obtained by turning the lamp in its stand, which is eccentric (Fig. 34).

Finally, before taking an observation, one must wait some ten minutes for the lamp to come into heat equilibrium; then only does the flame possess a constant brightness.

FIG. 34.

Measurements.—In order to take an observation, a body selected as standard, as the flame of a stearine candle or the flame of a kerosene lamp, is examined; one observes:

1. n_0, the number of absorbing-glasses;
2. d_0, the aperture of the cat's-eye;
3. f_0, the extension of the objective for focussing.

The same process is followed for the source to be studied, and the numbers n_1, d_1, f_1 are found.

k being the absorption coefficient of the tinted glasses, we have:

$$\frac{I}{1} = \left(\frac{1}{k}\right)^{(n_1 - n_0)} \cdot \left(\frac{d_0}{d_1}\right)^2 \cdot \left(\frac{f_1}{f_0}\right)^2.$$

For the glasses mentioned, the absorption coefficients are:

$$k = \tfrac{1}{11}, \text{ corresponding to } \lambda = 659;$$
$$k = \tfrac{1}{7}, \qquad `` \qquad `` \lambda = 546;$$
$$k = \tfrac{1}{10}, \qquad `` \qquad `` \lambda = 460.$$

For very small objects which would have to be placed very near, a supplementary objective is put in front of the telescope; the object is placed in the principal focus of this new lens, the objective of the apparatus being focussed for parallel rays. The absorptive power of this supplementary lens is reckoned as $\tfrac{1}{10}$.

Details of an Observation.—The first operation to make is the determination of the absorption coefficients of the absorbing-glasses. For that, one views an object of suitable intensity once with the tinted glass before the cat's-eye and then without this glass. Let N be the aperture of the cat's-eye without tinted glass, and N' the aperture with such a glass. The coefficient K of absorption is

$$K = \left(\frac{N'}{N}\right)^2.$$

The following observations furnish data for the determination of the absorbing powers of different glasses employed in the course of studies relative to the radiations from incandescent mantles.

Emissive Power.—Before being able to establish the relation which exists between the intensity of radiation of incandescent bodies and their temperature, it is necessary to know the emissive powers of these bodies. For this measurement use is made of the principle stated above, that the interior of fissures in bodies may be considered as enclosed in an envelope at uniform temperature. The emissive power is thus, at the temperature considered,

equal to the ratio of the luminous intensity of the surface to that of the bottom of deep fissures, with the condition, evidently, that the aperture of the fissures be sufficiently small.

ABSORBING-GLASS PLACED BEFORE THE SOURCE TO BE STUDIED.

Temperature.	Aperture of Cat's-eye.		
	Red.	Green.	Blue.
1270° (+ 1 glass).........	19.5	21.2	35
1270 (no glass)...........	5.5	7.9	11.1
	$k_r^? = 12.5$	$k_g = 7.2$	$k_b = 9.9$

ABSORBING-GLASS PLACED BEFORE THE STANDARD LAMP.

1170° (− 1 glass).........	2.9	5.95	10.2
1170 (no glass)...........	9.4	16.1	31.5
	$k_r = 10.5$	$k_g = 7.3$	$k_b = 9.5$

The body to be studied was placed in the state of a paste, as dry as possible, on the end of a couple previously flattened so as to take the form of a disk of 2 or 3 mm. diameter. The drying was very slow, so as not to have any swelling of the mass, and one obtained in this way a coating possessing fissures; the conditions described above are then satisfied. The end of the couple thus prepared is heated either in a Bunsen flame or a blast-lamp, and the temperature of the junction is noted, while, simultaneously, read are taken with the optical pyrometer. In order to obtain a temperature as constant as possible, it is necessary to guard against currents of air and use a flame of small size.

Here are some results obtained:

I. COUPLE COVERED WITH A MIXTURE CONTAINING 99 PARTS OF
THORIUM AND 1 OF CERIUM.

Temperatures.	Red. (1)	Red. (2)	Green. (1)	Green. (2)	Blue. (1)	Blue. (2)
950° (− 1 glass)........	16.0	...	21.0	14.0	23.0	
1170	15.5	9.0	11.0	9.0	12.0	12.0
1375	7.0	3.0	4.5	3.2	3.5	3.5
1525	3.2	2.0	2.0	2.0	1.9	1.9
1650 (+ 1 glass).......	8.3	6.0	5.0	....	4.0	

II. MAGNESIA.

	Red. (1)	Red. (2)	Green. (1)	Green. (2)	Blue. (1)	Blue. (2)
1340° (− 1 glass).......	12.2	4.0	18.5	6.7	19.0	9.0
1460 (− 1 glass)......	4.9	2.5	8.2	3.1	7.7	4.1
1540 (− 1 glass).......	2.4	1.3	3.1	1.8	3.2	2.1

The numbers give the divisions of the cat's-eye; those of column (1) refer to the surface, and those of column (2) to the bottom of the fissures. The indications (− 1 glass) and (+ 1 glass) mean that the absorbing-glass is placed either before the standard lamp or before the source studied.

Measurements of Intensity.—The following table gives an idea of the order of magnitude of the intensities of different luminous sources, the measurements of brightness being made in the red. Unity is the brightness of the axial portion of stearine candle-flame.

Carbon beginning to glow (600°).............	0.0001
Silver melting (950°)......................	0.015
Stearine candle, Gas-flame, Acetate of amyl lamp, }	1.0
Pigeon-lamp, with mineral oil..............	1.1
Argand burner, with chimney..............	1.9
Auer burner..............................	2.05
Fe_3O_4 melting (1350°)....,...............	2.25
Palladium melting.........................	4.8
Platinum melting..........................	15.0
Incandescent lamp........................	40
Crater of electric arc........ 10,000	
Sun at midday............, ...90,000	

Graduation.—Le Chatelier made a first graduation of the optical pyrometer by measuring the brightness of iron oxide heated on the junction of a thermoelectric couple, and admitting that, for the red, the emissive power of this substance is equal to unity. He found a law of variation of the intensity of the red radiations as function of the temperature, which is well represented by the formula

$$I = 10^{6.7} \cdot T - \frac{3210}{T},$$

in which unit intensity corresponds to the most brilliant axial region of the flame of a candle. (*T* is absolute temperature.)

The table below gives, for intervals of 100°, the intensities of red radiations emitted by bodies of an emissive power equal to unity. These numbers were calculated by means of the interpolation formula given above.

Intensities.	Temperatures.	Intensities.	Temperatures.
0.00008	600°	39	1800°
.00073	700	60	1900
.0046	800	93	2000
.020	900	1,800	3000
.078	1000	9,700	4000
.24	1100	28,000	5000
.64	1200	56,000	6000
1.63	1300	100,000	7000
3.35	1400	150,000	8000
6.7	1500	224,000	9000
12.9	1600	305,000	10000
22.4	1700		

These results are represented graphically in Fig. 35.

After having determined the value of the diaphragm d_0, which gives equality of brightness of the standard candle with that of the comparison-lamp, and the absorbing power k of the tinted glasses, one may, as was said before, prepare

a table which gives directly the temperature corresponding to each aperture of the cat's-eye.
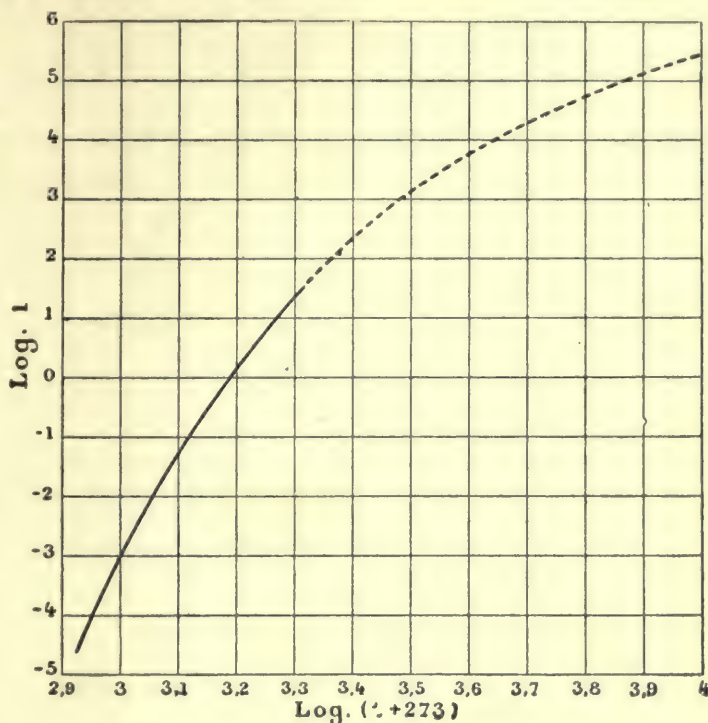
FIG. 35.

With an apparatus for which

$$d_0 = 5.2, \quad k = \tfrac{1}{11},$$

the following table is obtained, in which the plus sign refers to tinted glasses placed before the objective, and the minus sign to those before the lamp.

This graduation applies to all bodies placed in an enclosure at the same temperature, in the interior of furnaces for example, and to black bodies whatever the temperature surrounding them, for example a piece of red-hot iron exposed to the free air. For bodies whose emissive power is inferior to unity as platinum, magnesia, lime, it is neces-

sary, when they are exposed to the air and not surrounded by an enclosure at the same temperature, to make a special graduation.

Temperatures.	— 2 Glasses.	— 1 Glass.	0 Glass.	+ 1 Glass.	+ 2 Glasses.
700°	17.3	....	....	....	....
800	6.9	23.0	....	....	....
900	....	11.0	....	....	....
1000	....	5.6	18.6	....	....
1100	....	....	10.5	....	....
1200	....	....	6.5	....	....
1300	....	....	4.0	13.6	....
1400	....	....	....	9.4	....
1500	....	....	....	6.6	....
1600	....	....	....	4.8	....
1700	....	....	....	3.6	12.0
1800	....	....	....	....	9.1
1900	....	....	....	....	7.3
2000	....	....	....	....	5.9

(Aperture of the Cat's-eye)

Le Chatelier and Boudouard have made a series of measurements on radiations of different wave-lengths. The junction of a thermoelectric couple was placed in a small platinum tube, to realize approximately an enclosed space. By taking as unity the brightness of melting platinum, the results obtained are the following for the red, green, and blue radiations:

t	Log $(t + 273)$	I_r	Log I_r	I_v	Log I_v	I_b	Log I_b
900°	3.0707	0.0009	$\bar{4}.95$	0.00018	$\bar{4}.25$	0.00002	$\bar{5}.3$
1180	3.161	.0024	$\bar{3}.88$	.0087	$\bar{3}.94$	.0015	$\bar{3}.17$
1275	3.190	.075	$\bar{2}.78$	.037	$\bar{2}.57$	.013	$\bar{2}.11$
1430	3.230	.23	$\bar{1}.36$	.16	$\bar{1}.67$	.058	$\bar{2}.76$
1565	3.265	.72	$\bar{1}.86$	.47	$\bar{1}.20$	.24	$\bar{1}.38$
1715	3.300	1.69	0.23	1.45	0.16	.9	$\bar{0}.95$

Evaluation of Temperatures.—Finally, Le Chatelier has used his optical pyrometer to determine the very highest temperatures realized in some of the most important phenomena in nature or in the industries. These results,

quite different from previous determinations, were at first regarded with considerable reserve; they are admitted to-day as exact, at least within the limits of precision. Here are some of the figures obtained:

Siemens-Martin furnace...............	1490° to 1580°
Furnace of glass-works	1375 to 1400
Furnace for hard porcelain	1370
" " new porcelain.............	1250
Incandescent lamp....................	1800
Arc lamp............................	4100
Sun.................................	7600

This determination of the temperature of the sun has been confirmed by the more recent experiments of Wilson and Gray (page 165) by a totally different method.

A series of measurements were made with the same apparatus in iron-works. Here are some results:

BLAST-FURNACE FOR BESSEMER CASTING.

Crucible before the blast-pipe...................	1930°
Flow of the casting, beginning...................	1400
" " " " end...	1520

BESSEMER CONVERTER.

Flow of the scoria.............................	1580°
" " " steel into the pocket...............	1640
" " " " " " moulds...............	1580
Reheating of the ingot........................	1200
End of the hammering.	1080

SIEMENS-MARTIN FURNACE.

Flow of the steel into the pocket, beginning......	1580°
" " " " " " " end............	1420
" into the moulds........................	1490

Conditions of Use.—The optical pyrometer, by reason of the uncertainty of emissive powers and of the slight sensibility of the eye for comparisons of luminous intensities, cannot give as accurate results as other pyrometric

methods. Its use should be limited to the cases in which other methods necessarily fail; for example, in the case of a moving body, as a rail passing into the rolling-mill; in the case of very high temperatures superior to the fusing-point of platinum, as of the crucible of the blast-furnace or that of the electric furnace; in the case of isolated bodies radiating freely into the air, as flames or wires heated by an electric current which cannot be touched without changing their temperature.

It is also convenient in the case of strongly heated furnaces, as steel and porcelain furnaces. But in this usage care must be taken to guard against the brightness of the flames, always hotter than the furnace, and against the entry of cold air. The arrangement with the closed tube described in connection with the heat-radiation pyrometer is indispensable if it is desired to obtain anywhere near exact results. Compared to this last pyrometer, the optical pyrometer has the advantage to be much simpler and less costly, and to require no installation in a fixed position. It has, on the other hand, the inconvenience to require a more active intervention on the part of the operator and can hardly be intrusted to a workman, while the set-up of the heat-radiation pyrometer may be made so that an observation reduces to a reading upon a scale.

Measurement of the Relative Intensity of Different Radiations.—It is on this principle that rests the eye-estimation of temperatures, such as are made by workmen in industrial works. Numerous attempts, none very successful, have been made to modify this method and make it precise. There is need to consider this only from the point of view of a summary control over the heating of industrial furnaces.

a. Use of the Eye.—Pouillet made a comparison of the colors of incandescent bodies in terms of the air-thermom-

eter. The table that he drew up is reproduced everywhere to-day:

First visible red........	525°	Dull orange.............	1100°
Dull red..............	700	Bright orange...........	1200
Turning to cherry......	800	White.................	1300
Cherry proper..........	900	Melting white...........	1400
Bright cherry..........	1000	Dazzling white....	1500

The estimation of these hues, very arbitrary and varies from one person to another; more than that, it varies for the same person with the exterior lighting. The hues are different by day from those by night; it is thus that the gas-flame, yellow during the day, appears white at night.

b. Use of Cobalt Glass. — One may exaggerate the changes of hue in suppressing from the spectrum the central radiations, the yellow and green for example, so as only to keep the red and the blue. The relative variations of two hues are the greater the more separated they are in the spectrum; now, the red and the blue form the two extremities of the visible spectrum.

It has been proposed for this purpose to use cobalt glass, which cuts out the yellow and green, but lets pass the red and blue. It must be noticed in the first place that the ratio of the radiations transmitted varies with the thickness of the glass as well as their absolute intensity.

Let I_a and I_b be the intensities of the radiations emitted, k_a and k_b the proportions transmitted by the glass through a thickness 1. Through a thickness e the proportion transmitted will be

$$\frac{I_a k_a^e}{I_b k_b},$$

which will vary with e in all cases that k_a is different from k_b.

It results from this that two cobalt glasses, differing in thickness or in amount of cobalt, will not give the same

results. So that if the cobalt glass habitually used is broken, all the training of the eye goes for naught.

Besides, cobalt has the inconvenience of having an insufficient absorbing power for the red, which predominates at the more ordinary temperatures that we make use of. It would be possible without doubt, by the addition of copper oxide, to augment the absorbing power for the red.

One would have better and more comparable results by employing solutions of metallic salts or of organic compounds suitably chosen. But few trials have been made in this matter.

Apparatus of Mesuré and Nouel.—It is known that by placing between two nicols a plate of quartz cut perpendicular to the axis a certain number of the radiations of the spectrum are suppressed. This latter is then composed of dark bands whose spacing depends on the thickness of the quartz and the position of the angle of the nicols. Mesuré and Nouel have utilized this principle in order to cut out the central portions of the spectrum; this solution is excellent and preferable to the use of absorbing media. The apparatus (Fig. 36) consists essentially of a polarizer P and an
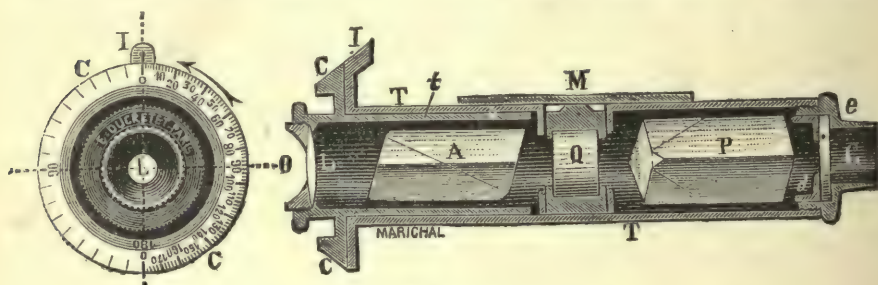
FIG. 36.

analyzer A, whose adjustment to extinction gives the zero of graduation of the divided circle CC. This circle is graduated in degrees and is movable before a fixed index I. Between the two nicols P and A is a quartz Q of suitable

thickness, carefully calibrated. The mounting M allows of its quick removal if it is necessary to verify thead just-ment of the nicols P and A. The quartz Q is cut perpen-dicularly to the axis. A lens L views the opposite opening C furnished with a parallel-faced plate glass or, where desired, with a diffusing-glass very slightly ground.

The relative proportions of various rays that an incan-descent body emits varying with the temperature, it follows that for a given position of the analyzer A the composite tint obtained is different for different temperatures.

If the analyzer is turned while a given luminous body is received, it is noticed that the variations of colora-tion are much more rapid for a certain position of the analyzer. A very slight rotation changes suddenly the color from red to green. Now, if the analyzer is left fixed, a slight variation in the temperature of the incandescent body produces the same effect. The transition hue red-green constitutes what is called the sensitive hue. There are then two absorptions, one in the yellow and the other in the violet.

This apparatus may be employed in two different ways. First fix permanently the analyzer in a position which gives the sensitive hue for the temperature that is to be watched, and observe the changes of hue which are produced when the temperature varies in one sense or the other from the type temperature. This is the ordinary method of use of this instrument. It is desired in a given manufacturing process (steel, glass) to make sure that the temperature of the furnace rests always the same; the instrument is ad-justed once for all for this temperature. It suffices to have but a short experience to train the eye to appreciate the direction of the changes of hue.

The inventors have sought to make of their apparatus a measuring instrument; this idea is quite open to de-

bate.   In theory this is easy; it suffices, instead of having
the analyzer fixed, to make it turn just to the securing of
the sensitive hue and to note the angle which gives the
position of the analyzer.   But in fact the sensitive hue is
not rigorously determinate and varies with the observer.
A graduation made by one observer will not hold for
another.   It is not even certain that the same observer will
choose always the same sensitive hue.   At each tempera-
ture the sensitive hue is slightly different, and it is im-
possible to remember throughout the scale of temperatures
the hues that were chosen on the day of the graduation.
There is even considerable difficulty to recall this for a
single temperature.

The following figures will give an idea of the differences
which may exist between two observers as to the position
of the sensitive hue:

	Temperature.	Angle of Analyzer.	
		(1)	(2)
Sun	8000°	84	86
Gas-flame	1680	65	70
Red-hot platinum	800	40	45

The errors in the estimation of temperatures which
result from the uncertainty of the sensitive hue will thus
exceed 100°.   With observers having had more experience
the difference will be somewhat reduced, but it will remain
always quite large.

Pyrometer of Crova.—Crova has endeavored to give to
the method of estimation of temperatures based on the
unequal variation of different radiations of the spectrum a
scientific precision by measuring the absolute intensity of
each of the two radiations utilized; but this method, from
the practical point of view, does not seem to have given
more exact results than the preceding ones.

The eye is much less sensitive to difference of intensity

than to difference of hue, so that there is no advantage to make use of observations of intensity.

Crova compares two radiations,

$$\lambda = 676 \text{ (red)},$$
$$\lambda = 523 \text{ (green)},$$

coming from the object studied and from the oil-lamp used as standard. For this purpose, by means of a variable diaphragm, he brings to equality one of the two radiations emanating from each of the sources, and measures afterwards the ratio of the intensities of the two other radiations.

The apparatus is a spectrophotometer. Placed before half the height of the flame is a total reflecting prism, which reflects the light from a ground glass, lighted by the radiations from an oil-lamp, having first passed through two nicols and a diaphragm of variable aperture. On the other half of the slit is projected by means of a lens the image of the body to be studied.

Before using the apparatus it is necessary to adjust the extreme limits of the displacement of the spectrum so as to project successively on the slit, in the focus of the eye-piece, the two radiations selected ($\lambda = 676$ and $\lambda = 523$). For this purpose there is interposed between the two crossed nicols a 4-mm. quartz plate which re-establishes the illuminations; for extinction again, the analyzer must be turned 115° 38' for $\lambda = 523$, and 65° 52' for $\lambda = 676$. The instrument is then so adjusted that the dark band produced by the quartz is situated in the middle of the ocular slit.

The apparatus thus adjusted, in order to make a measurement at low temperatures inferior to those of carbon burning in the standard lamp, one brings to equality the red radiation with the diaphragm, then, without touching the diaphragm again, one brings the green to equality by turning the nicol.

The optical degree is given by the formula

$$N = 1000 \cos^2 \alpha,$$

denoting by α the angle between the two principal sections of the nicols.

For higher temperatures the operation is reversed; one brings first the green to equality by means of the diaphragm, then the red to equality by a rotation of the analyzer. The optical degree is then given by the formula $N = \dfrac{1000}{\cos^2 \alpha}$, and the rotation varying from 0° to 90°, the optical degrees vary from 1000° to infinity.

This method, which is theoretically excellent, possesses certain practical disadvantages:

1. Lack of precision of the measurements. In admitting an error of 10 per cent in each one of the observations relative to the red and green radiations, the total possible error is 20 per cent; now, between 700° and 1500° the ratio of intensities varies from 1 to 5; this leads to a difference of $\frac{1}{2.5}$ in 800°, or 32°.

2. Complication and slowness of observations. It is difficult to focus exactly on the body or the point on the body that one wishes to study. The set-up and the taking of observations sometimes requires about half an hour.

3. Absence of comparison in terms of the air-thermometer.

The *à priori* reason that had led to the study of this method was the supposition that, in general, the emissive power of substances was the same for all radiations, and that consequently its influence would disappear by taking the ratio of the intensities of the two radiations. The measurements of emissive power given previously prove that this hypothesis is the more often inexact.

CHAPTER IX.

CONTRACTION PYROMETER (WEDGWOOD).

WEDGWOOD's pyrometer, the oldest among such instruments, presents to-day hardly more than an historic interest, for its use has been almost entirely abandoned. It utilizes the permanent contraction assumed by clayey matters under the influence of high temperature. This contraction is variable with the chemical nature of the paste, the size of the grains, the compactness of the wet paste, the time of heating, etc. In order to have comparable results, it would be necessary to prepare *simultaneously, under the same conditions,* a great quantity of cylinders, whose calibration would be made in terms of the air-thermometer. Wedgwood employed cylinders of fire-clay, baked until dehydrated, or to 600°; this preliminary baking is indispensable if one wishes to avoid their flying to pieces when suddenly submitted to the action of fire. These cylinders have a plane face on which they rest in the measuring apparatus, so as always to face the same way (see the frontispiece). The contraction is measured by means of a gauge formed by two inclined edges; two similar gauges of 6 inches in length, one an extension of the other, are placed side by side; at one end they have a maximum separation of 0.5 inch, and at the other a minimum separation of 0.3 inch. Longitudinally the divisions are of 0.05 inch; each division equals $\frac{1}{240}$ of $\frac{2}{10}$ of an inch, or $\frac{1}{1200}$ inch, which corresponds to a relative contraction of $\frac{1}{1200} \div \frac{5}{10} = \frac{1}{600}$ in terms of the initial dimensions.

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We then have the following relation between the Wedgwood degrees and the linear contraction per unit of length:

Wedgwood......	0	30	60	90	120	150	180	210	240
Contraction......	0	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40

Le Chatelier has made experiments to determine the degrees of the Wedgwood pyrometer in terms of the scale of the air-thermometer by making use of clayey substances of different kinds, and in the first place of the cylinders from an old Wedgwood pyrometer of the Ecole des Mines. The contraction which accompanies the dehydration is quite variable with the nature of the pastes. In these experiments the time of heating was half an hour.

Centigrade temperature.....	600°	800°	1000°	1200°	1400°	1550°
Wedgwood.................	0	4	15	36	90	132
Argile de Mussidan........	0	2	14	36	78	120
Limoges porcelain...........	0	0	2	21	88	91
Faïence de Choisy-le-Roi....	0	2	5	12	48	75
Faïence de Nevers..........	0	0	0	32	melted	melted
Kaolin................../.....	0	4	13	15	55	118
Clay.......... 25 ⎫ .... Titanic acid.... 75 ⎭	0	4	9	19	123	160

This table shows how variable are the observations; it is impossible, consequently, to compare the old measurements of Wedgwood and of his successors, because the manufacture of the cylinders has varied with the course of time.

Wedgwood had given a graduation made by a process of extrapolation which he has not explained, a graduation according to which he attributed 10,000° centigrade to 130° of his pyrometer, which corresponds to about 1550°. One might still seek to re-establish the graduation by utilizing the determinations of the fusing-points of the metals made by Wedgwood, but the results are too dis-

cordant to warrant any definite conclusion. According to Wedgwood, copper would be more fusible than silver, iron would not be far removed from silver; it is probable that these observations were made with very impure metals, or at any rate were made with metals much oxidized before their fusion. In any case the cylinders which he made use of in his first experiments assume a much greater contraction than those of the pyrometer of the School of Mines whose graduation was given above. One might with considerable reserve indicate the following graduation for measurements made with the first cylinders employed about 1780:

Wedgwood degrees............	0	15	30	100	140
Centigrade degrees............	600	800	1000	1200	1400

The preparation of the cylinders was a most care-taking operation. Moulded in soft paste they were necessarily somewhat irregular. After the first baking they had to be trimmed to bring them to a uniform size. To-day, in several pottery works where the method is still employed, a much greater regularity is obtained by using a very dry paste, 5 per cent of water for example, moulding it under great pressure, about a hundred kilogrammes per square centimeter, in moulds of turned steel. The precision of the measurements is increased by augmenting the diameter, to 50 mm. for example. It is necessary at the same time to reduce the thickness to about 5 mm., in order that the compression be uniform throughout the mass.

This apparatus cannot be recommended in any instance as a true pyrometer, serving indirectly to evaluate temperatures in terms of the air-thermometer scale. The graduation is laborious and can only be made by means of the intermediary of another pyrometer; the use of fixed points is not adapted for this graduation because the curve of contraction of clay in function of the temperature is too

irregular for two or three points to determine it; in no
case do the indications of this instrument possess any con-
siderable precision.

But as simple pyroscope, that is to say, as an apparatus
to indicate merely the equality or inequality of two tem-
peratures, the Wedgwood pyrometer is very convenient.
It has the advantage of costing almost nothing and it is
easy to use and within the comprehension of any workman.
It seems to be particularly recommendable for certain
ceramic industries, in which the ordinary pastes found
there may be used to make the contraction cylinders. It is
necessary for this that the normal baking of these pastes
is stopped at a temperature comprised within the period
of rapid contraction.   This is the case with fine faïence
and with ordinary earthenware.   That would not be the
case, however, for stanniferous faïence nor for porcelain,
because the baking of the first is stopped before the
beginning of the contraction, and that of the second after
its finish.

CHAPTER X.

FUSIBLE CONES (SEGER).

A LONG time ago it was proposed to compare temperatures by means of the fusing-points of certain metals and alloys. But the non-oxidizable metals are not numerous and all are very costly: silver, gold, palladium, platinum. Use has, however, been made sometimes of these metals and their alloys, in admitting that the fusing-point of a mixture of two substances is the arithmetical mean of the points of fusion of the components, which is not quite exact. The use of these alloys is entirely abandoned to-day, and with reason.

By making use of metallic salts, among which a great number may be heated without alteration, one might constitute a scale of fusing-points whose employ would be often very convenient; but this work is not yet done, at least not in a sufficiently precise manner. To the separate salts may be added their definite combinations and their eutectic mixtures which have prefectly definite fusing-points. But one cannot take any mixture whatever of two salts, because in general the solidification takes place throughout a large interval of temperature and in a progressive manner.

Instead of utilizing the fusion of crystallized substances which pass abruptly from the solid to the liquid state, use may be made of the progressive softening of vitreous matters, that is to say, of mixtures containing an excess

of one of the three acids, silicic, boric, or phosphoric. It is necessary in this case to have a definite process for defining a type degree of softening; a definite depression of a prism of given size is taken. These small prisms, formed of vitreous matters, are known under the name of *fusible cones.*

This method was first devised by Lauth and Vogt, who applied it in the manufactures at Sèvres before 1882. But they did not develop it as far as was possible; they were content to construct a small number of fusible cones corresponding to the various temperatures employed in the manufacture of the porcelain of Sèvres.

Seger, director of a research laboratory at the royal pottery works of Berlin, published, in 1886, an important memoir on this question. He determined a whole series of fusible cones of intervals of about 25°, including the interval of temperature from 600° to 1800°. The substances which enter into the composition of these cones are essentially:

Pure quartz sand;

Norwegian feldspar;

Pure carbonate of lime;

Zettlitz kaolin.

The composition of this last is:

$$SiO_2 \dots\dots\dots\dots\dots\dots\dots\dots\dots 46.9$$
$$Al_2O_3 \dots\dots\dots\dots\dots\dots\dots\dots\dots 38.6$$
$$FeO_3 \dots\dots\dots\dots\dots\dots\dots\dots\dots 0.8$$
$$Alkalies \dots\dots\dots\dots\dots\dots\dots\dots 1.1$$
$$Water \dots\dots\dots\dots\dots\dots\dots\dots\dots 12.7$$

In order to obtain very infusible cones, calcined alumina is added, and for very fusible cones oxide of iron, oxide of lead, carbonate of soda, and boric acid.

The shape of these cones (Fig. 37) is that of triangular pyramids of 15 mm. on a side and 50 mm. high. Under

the action of heat, when softening begins, they at first contract without change of form, then they tip, bending over, letting their apex turn downwards, and finally flatten-
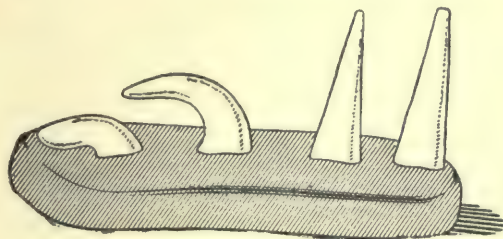
FIG. 37.

ing out completely. One says that the cone has fallen, or that it has melted, when it is bent half-way over, the point directed downwards.

The fusing-points of these substances have been determined at the Berlin porcelain works by comparison with the Le Chatelier thermoelectric pyrometer, previously described.

The cones are numbered, for the less fusible, which were first adjusted, from 1 to 38; this latter, the least fusible, corresponds to 1980°. The second series, more fusible, and established later, is numbered from 01 to 022; this last cone, the most fusible, corresponds to 590°.

If, instead of using the cones of German make, one wishes to make them himself in employing the same formulæ, it is prudent to make a new graduation. The kaolins and feldspars from different sources never have exactly the same compositions, and very slight variations in their amounts of contained alkali may cause marked changes in the fusibility, at least for the less fusible cones.

It is to be noticed that in a great number of cones silica and alumina are found in the proportions $Al_2O_3 + 10SiO_2$. This is for the reason that this mixture is more fusible

than can be had with silica and alumina alone. It is the starting-point to obtain the other cones, the less fusible by the addition of alumina, and the more fusible by the addition of alkaline bases.

The table on page 172 gives the list of cones of Seger's scale.

These cones may be classed in a series of groups in each of which the compositions of different cones are derived from that of one of them, generally the most fusible, by addition in varying proportions or sometimes by substitution of another substance.

The cones 28 to 38 are derived from the cone 27 by the addition of increasing quantities of Al_2O_3.

The cones 5 to 28 from the cone 5 by addition of increasing quantities of the mixture $Al_2O_3 + 10SiO_2$.

The cones 1 to 5 from the cone 1 by substitution of increasing quantities of alumina for the sesquioxide of iron.

The cones 010 to 1 from the cone 1 by the substitution of boric acid for silica.

The cones 022 to 011 from the cone 022 by the addition of increasing quantities of the mixture $Al_2O_3 + 2SiO_2$.

Fig. 38 gives the graphical representation of these data; the ordinates are temperatures, and the abscissæ are values of x from the table.

These fusible cones of Seger are pretty generally used in the ceramic industry; they are very convenient in all intermittent furnaces whose temperature has to increase constantly up to a certain maximum, at which point the cooling-off is allowed to commence. It is sufficient, before firing up, to place a certain number of fusible cones opposite a draft-hole closed by a glass through which they may be watched. In seeing them fall successively, one knows at what moments the furnace takes on a series of definite temperatures.

In continuous furnaces, the cones may be put into the furnace during the process, but that is more delicate. It
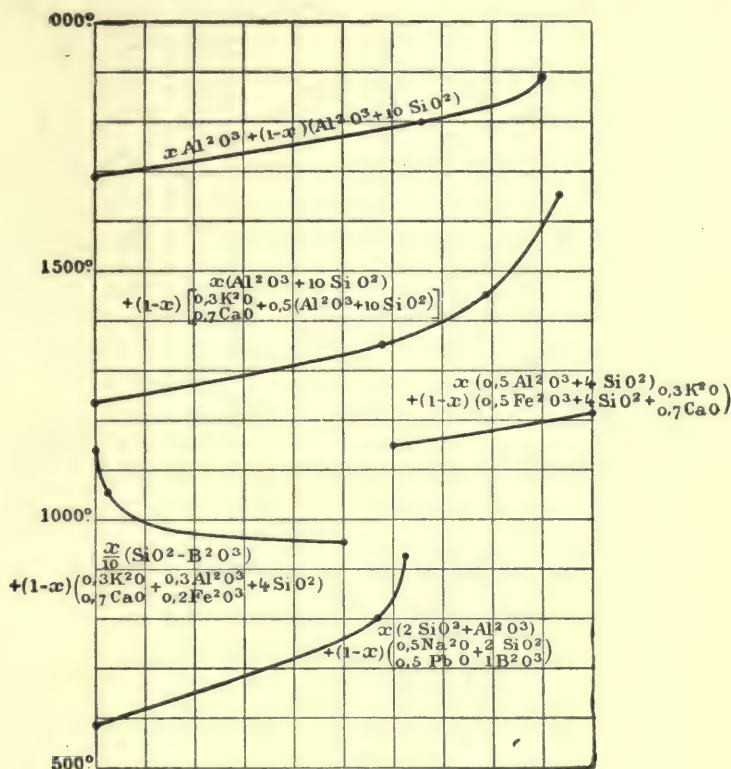
FIG. 38.

is necessary to place them on little earthenware supports that are moved into the desired part of the furnace by an iron rod. When, on the contrary, they are put in place at the start in the cold furnace, they are held in place by a small lump of clay.

Nos.	Deg. T.	Composition.	X	Formulæ.
38	1890	$1\ Al_2O_3 + 1\ SiO_2$	9	
36	1850	1 " $+ 1.5$ "	8	
35	1830	1 " $+ 2$ "		
34	1810	1 " $+ 2.5$ "		
33	1790	1 " $+ 3$ "		
32	1770	1 " $+ 4$ "		$X\,Al_2O_3$
31	1750	1 " $+ 5$ "		$+ (1-X)(Al_2O_3 + 10SiO_2)$
30	1730	1 " $+ 6$ "		
29	1710	1 " $+ 8$ "		
28	1690	1 " $+ 10$ "		
27	1670	$1 \begin{Bmatrix} 0.3\ K_2O \\ 0.7\ CaO \end{Bmatrix} + 20(Al_2O_3 + 10SiO_2)$	0	
26	1650	1 " $+ 7.2$ "	93	
25	1630	1 " $+ 6.6$ "		
24	1610	1 " $+ 6$ "		
23	1590	1 " $+ 5.4$ "		
22	1570	1 " $+ 4.9$ "		
21	1550	1 " $+ 4.4$ "		
20	1530	1 " $+ 3.9$ "		
19	1510	1 " $+ 3.5$ "		
18	1490	1 " $+ 3.1$ "		$X(Al_2O_3 + 10\ SiO_2)$
17	1470	1 " $+ 2.7$ "	79	$+ (1-X)\begin{pmatrix} 0.3\ K_2O \\ 0.7\ CaO \end{pmatrix}$
16	1450	1 " $+ 2.4$ "		
15	1430	1 " $+ 2.1$ "		$+ 0.5(Al_2O_3 + 10SiO_2))$
14	1410	1 " $+ 1.8$ "		
13	1390	1 " $+ 1.6$ "		
12	1370	1 " $+ 1.4$ "		
11	1350	1 " $+ 1.2$ "	58	
10	1330	1 " $+ 1$ "		
9	1310	1 " $+ 0.9$ "		
8	1290	1 " $+ 0.8$ "		
7	1270	1 " $+ 0.7$ "		
6	1250	1 " $+ 0.6$ "		
5	1230	1 " $+ 0.5$ "	0	
4	1210	1 " $+ 0.5\ Al_2O_3 + 4\ SiO_2$	1	
3	1190	1 " $+ \begin{Bmatrix} 0.45\ Al_2O_3 \\ 0.05\ Fe_2O_3 \end{Bmatrix} + 4\ SiO_2$		$X(0.5\ Al_2O_3 + 4\ SiO_2)$
2	1170	1 " $+ \begin{Bmatrix} 0.4\ Al_2O_3 \\ 0.1\ Fe_2O_3 \end{Bmatrix} + 4\ SiO_2$		$+ (1-X).(0.5\ Fe_2O$
1	1150	1 " $+ \begin{Bmatrix} 0.3\ Al_2O_3 \\ 0.2\ Fe_2O_3 \end{Bmatrix} + 4\ SiO_2$		$+ 4\ SiO_2 + 0.7\ CaO)$
01	1130	1 " $+$ " $+ \begin{Bmatrix} 3.95\ SiO_2 \\ 0.05\ B_2O_3 \end{Bmatrix}$	1.05	
02	1110	1 " $+$ " $+ \begin{Bmatrix} 3.90\ SiO_2 \\ 0.10\ B_2O_3 \end{Bmatrix}$		
03	1090	1 " $+$ " $+ \begin{Bmatrix} 3.85\ SiO_2 \\ 0.15\ B_2O_3 \end{Bmatrix}$		
04	1070	1 " $+$ " $+ \begin{Bmatrix} 3.80\ SiO_2 \\ 0.20\ B_2O_3 \end{Bmatrix}$		$\dfrac{X}{10}(SiO_2 - B_2O_3)$
05	1050	1 " $+1$ " $+ \begin{Bmatrix} 3.75\ SiO_2 \\ 0.25\ B_2O_3 \end{Bmatrix}$	1.25	$+ (1-X)\begin{pmatrix} 0.3\ K_2O \\ 0.7\ CaO \end{pmatrix}$
06	1030	1 " $+1$ " $+ \begin{Bmatrix} 3.70\ SiO_2 \\ 0.30\ B_2O_3 \end{Bmatrix}$		$+ \begin{Bmatrix} 0.3\ Al_2O_3 \\ 0.2\ Fe_2O_3 \end{Bmatrix} + 4\ SiO_2)$
07	1010	1 " $+1$ " $+ \begin{Bmatrix} 3.65\ SiO_2 \\ 0.35\ B_2O_3 \end{Bmatrix}$		
08	990	1 " $+1$ " $+ \begin{Bmatrix} 3.60\ SiO_2 \\ 0.40\ B_2O_3 \end{Bmatrix}$		
09	970	1 " $+1$ " $+ \begin{Bmatrix} 3.55\ SiO_2 \\ 0.45\ B_2O_3 \end{Bmatrix}$		
010	950	1 " $+1$ " $+ \begin{Bmatrix} 3.5\ SiO_2 \\ 0.5\ B_2O_3 \end{Bmatrix}$	5	

Nos.	Deg. T.	Composition.			X	Formulæ.
011	920	$1 \begin{Bmatrix} 0.5\ Na_2O \\ 0.5\ PbO \end{Bmatrix}$	$+\ 0.8\ Al_2O_3\ +$	$\begin{Bmatrix} 3.6\ SiO_2 \\ 1.0\ B_2O_3 \end{Bmatrix}$	0.61	
012	890	1 "	$+\ 0.75$ " $+$	$\begin{Bmatrix} 3.5\ SiO_2 \\ 1.0\ B_2O_3 \end{Bmatrix}$		
013	860	1 "	$+\ 0.70$ " $+$	$\begin{Bmatrix} 3.4\ SiO_2 \\ 1.0\ B_2O_3 \end{Bmatrix}$		
014	830	1 "	$+\ 0.65$ " $+$	$\begin{Bmatrix} 3.3\ SiO_2 \\ 1.0\ B_2O_3 \end{Bmatrix}$		
015	800	1 "	$+\ 0.60$ " $+$	$\begin{Bmatrix} 3.2\ SiO_2 \\ 1.0\ B_2O_3 \end{Bmatrix}$	0.57	$X(2\,SiO_2 + Al_2O_3)$ $+\ (1-X)\Big(\begin{Bmatrix} 0.5\ Na_2O \\ 0.5\ PbO_3 \end{Bmatrix}$ $+ \begin{Bmatrix} 2\ SiO_2 \\ 1\ B_2O_9 \end{Bmatrix} \Big)$
016	770	1 "	$+\ 0.55$ " $+$	$\begin{Bmatrix} 3.1\ SiO_2 \\ 1.0\ B_2O_3 \end{Bmatrix}$		
017	740	1 "	$+\ 0.50$ " $+$	$\begin{Bmatrix} 3.0\ SiO_2 \\ 1.0\ B_2O_3 \end{Bmatrix}$		
018	710	1 "	$+\ 0.40$ " $+$	$\begin{Bmatrix} 2.8\ SiO_2 \\ 1.0\ B_2O_3 \end{Bmatrix}$		
019	680	1 "	$+\ 0.30$ " $+$	$\begin{Bmatrix} 2.6\ SiO_2 \\ 1.0\ B_2O_3 \end{Bmatrix}$		
020	650	1 "	$+\ 0.20$ " $+$	$\begin{Bmatrix} 2.4\ SiO_2 \\ 1.0\ B_2O_3 \end{Bmatrix}$		
021	620	1 "	$+\ 0.10$ " $+$	$\begin{Bmatrix} 2.2\ SiO_2 \\ 1.0\ B_2O_3 \end{Bmatrix}$		
022	590	1 "	$+$	$\begin{Bmatrix} 2.0\ SiO_2 \\ 1.0\ B_2O_3 \end{Bmatrix}$	0	

CHAPTER XI.

RECORDING PYROMETERS.

AMONG the different methods for the measurement of high temperatures, some of them may be made continuously recording. This recording is as useful for industrial applications as for scientific investigations. In research laboratories one endeavors as much as possible to take observations automatically, escaping the influence either of preconceived ideas or of carelessness of the observer; in industrial works the use of such processes gives continuous control over the work of the artisans, such as the presence of no foreman can replace.

The record may be made by means of a pen or by photography. The former of these methods, more simple to handle, is preferable in works; the second, whose indications are more precise, is preferable in the laboratory. In general, however, one has not the choice, each phenomenon utilized in the measurements being treatable by only one method of registering. So far, only three among the different pyrometers have been rendered recording:

The gas-thermometer at constant volume;

The thermoelectric pyrometer;

The electrical-resistance pyrometer.

But practically, up to now, the thermoelectric pyrometer alone has been used to take continuous records.

Recording Gas-pyrometer.—The transformation of the gas-thermometer into a recording instrument is extremely

simple and has been long since effected. It suffices to join permanently the tube from the porcelain bulb to a registering manometer to realize a recording pyrometer theoretically perfect. But practically these instruments possess many disadvantages that have prevented their introduction generally.

Above 1000° the permeability of the porcelain for water-vapor is sufficient to soon render them useless. Investigations made by the Paris Gas Company have shown that in furnaces heated to 1100° the penetration of water-vapor is sufficiently rapid so that in a few days liquid water collects in the cold parts of the apparatus.

Absolute impermeability of the apparatus, which is quite indispensable since its operation supposes the invariability of the gaseous mass, is very difficult to obtain. Frequently the glazing of the porcelain has holes in it. The numerous joints entering into the registering apparatus, and above all the metallic parts of the apparatus, may be the seats of very small leakages difficult to locate.

The connection of the metallic parts with the porcelain tube is generally made with wax, always with substances of organic origin which, in the vicinity of industrial apparatus, generally bulky and thick-walled, cannot be protected against radiation save by a water-jacket. This is a serious inconvenience.

In laboratory apparatus of small size the protection of the joint is easier, but then the large dimensions of the bulb, as has been indicated, are a serious disadvantage. One cannot, in a small furnace, find a large volume whose temperature is uniform.

But the most serious disadvantage of the recording gas-pyrometer, and the principal reason for its abandonment, is the difficulty of its graduation. Already with the mercury-manometer the waste space is a source

of complications. However, this may be measured and allowed for. With the registering manometer the waste space is much greater, and besides variable with the deformation of the elastic tube. Thus the graduation can be made only empirically, employing baths of fixed fusing- or boiling-points, an operation almost always impossible of realization with an apparatus of very fragile porcelain.
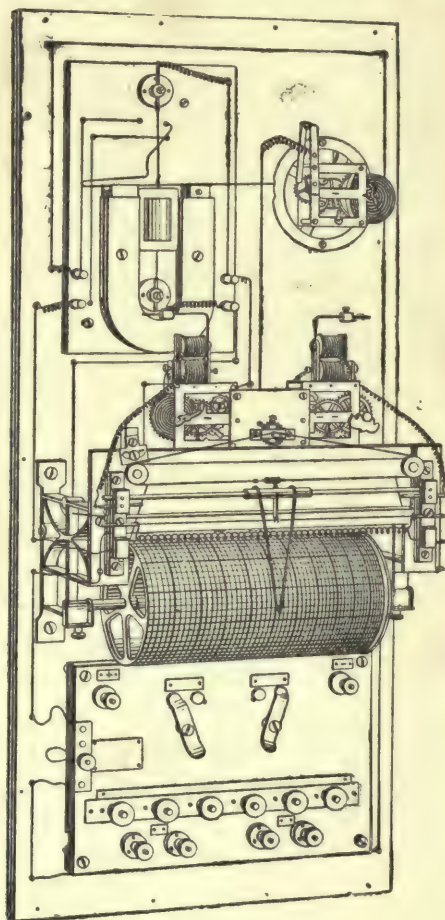
Fig. 39.

Electrical-resistance Recording-pyrometer.—After the gas-pyrometer, the oldest, we shall describe immediately

the electrical-resistance pyrometer, which is the most recent. It has not yet been used, and for this reason there is little to say regarding it.

In order to render his pyrometer recording (Fig. 39), Callendar employs the following very simple device. Two of the branches of a Wheatstone bridge used to measure the resistance of the heated coil are made of a single wire, on which slides a rider to which is brought one of the galvanometer leads. To each position of the rider, when the galvanometer is at zero, corresponds a resistance, and consequently a definite temperature of the coil. The position of the rider may be easily registered by attaching to it a pen writing on a sheet of paper which moves perpendicularly to the length of the wire. In order to have the curve thus obtained correspond to that of temperatures, it suffices that the position of the rider be at each instant adjusted so as to keep the galvanometer at zero.

This result is obtained by means of a clock-movement controlled by a relay that the galvanometer works in one direction or the other according to the direction of the deflection that it tends to take on from the zero-point. It is a movable-coil galvanometer whose needle carries an arm which, making contact, causes a current to pass.

Fig. 40 gives an example of a curve recorded by this apparatus.

This complicated registering apparatus is necessarily very costly, but it is actually the only one which effects the record of high temperatures by purely mechanical means, without the intervention of photography; it is possible that it will be used in certain large industrial works. For work in the laboratory it seems less convenient; the registering deprives the method of electrical resistances of the great precision which belongs to it and in which consists its great

merit; there are also disadvantages such as the necessity to use for the protection of the coil a fragile tube of porcelain of considerable volume.

This recorder possesses an interesting detail which

FIG. 40.

assures good working and which could well be adopted in other similar cases. The pointer of the galvanometer-needle does not hit against a fixed conductor to which it would stick on account of heating by the passage of the current and especially the extra current at break. This conductor consists of the metallic circumference of a wheel which is given a slow constant rotary motion, rendering all adherence impossible. This artifice renders possible working the relays by means of a sensitive galvanometer, which would not otherwise be realizable.

Callendar has applied the same method of recording to

Langley's bolometer. The curve of Fig. 41 gives the record of solar radiation for a day.
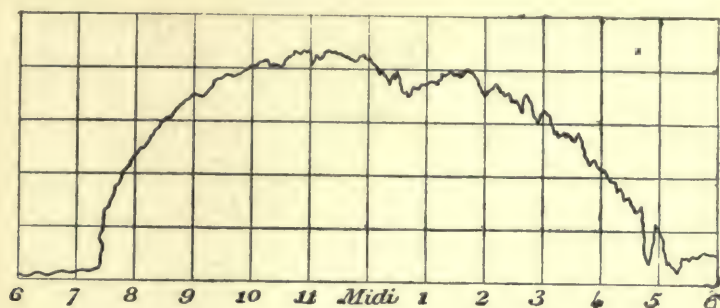
Theoretically, at least, the same method of recording may be applied to the measurement of temperatures by means of thermoelectric couples by using the method of opposition. But in this case the strength of the currents available to work the relays is much more feeble than in the preceding applications, and it is not certain that a sufficient sensibility can be obtained.

Thermoelectric Recording-pyrometer. — The only recording-pyrometers currently in use to-day are the thermoelectric pyrometers recording photographically. Numerous attempts have been made to secure a recorder with a pen, as is done in the case of the recording-voltmeters and ammeters in use industrially, but, up to the present, without success. The strengths of current which can be utilized are too weak; for a precision of $10°$ an apparatus sensible to $\frac{1}{10000}$ volt is necessary; the resistance of the galvanometer-coils should be considerable, 100 ohms at least, as has been previously explained, and the corresponding current will be only a millionth of an ampere. There are on the market such alleged recording-pyrometers, but they are constructed with galvanometer-coils of but few

ohms' resistance and cannot give measurements of temperature exact to 100°.

For the recording of temperatures one may seek two quite different results, to which are appropriate two methods of recording equally different. One may desire to determine the temperature at a definite epoch, that is to say, to trace the temperature curve in function of the time. This will be almost always the object in view in industrial works. It suffices, in this case, to let fall the luminous beam reflected by the galvanometer-mirror on a sensitive plate possessing a vertical movement of translation. The two coordinates of the curve thus recorded give, the one temperature, the other time. One may desire, on the other hand, to know the rate of variation of the temperature at a given instant, and at the same time the corresponding value of the temperature. This is the case in the greater number of laboratory investigations in which is desired the temperature at which a definite phenomenon occurs: fusion, allotropic transformation, etc.; and in order to recognize the occurrence of this phenomenon, use is ordinarily of the accompanying absorption or liberation of latent heat, which is manifested by a variation in the law of heating or of cooling.

It is this latter method of recording that Le Chatelier first developed during his investigations on clays. A luminous beam reflected by the galvanometer-mirror falls periodically at regular intervals, of a second for instance, upon a fixed sensitive plate. The distance apart of two successive images gives the variation of temperature during unit time, that is, the rate of heating or of cooling; the distance of the same image to the image corresponding to the beginning of the heating will give the measurement of the temperature.

In all cases of photographic recording it is necessary to,

replace the ordinary galvanometer-mirrors, which give images quite insufficient as to definition and brightness, by special mirrors made of a plane convex lens, silvered on the plane surface. These mirrors are slightly heavier than parallel-face mirrors, but have two important advantages: the absence of extra images reflected by the front surface of the mirror, and a greater rigidity which obviates accidental bendings of the mirror arising from the attachments to its support. One may easily get good mirrors of this type of 20 mm. diameter, and with more difficulty of 30 mm. diameter. These last give nine times more light than the mirrors ordinarily employed. It is easy to so choose the lens as to give a mirror of desired focal length. A plane convex lens whose principal focus by transmission is 1 m. will give, after silvering the plane surface, an optical system equivalent to a parallel-faced mirror whose radius of curvature would be 1 m.

Discontinuous Recording.—In this manner of recording the *luminous source* should possess periodic variations; one of the simplest to employ is the electric spark between two metallic points. The interruption of the current is produced by a pendulum at definite intervals of time.

In order to have a spark sufficiently bright, it is necessary to use an induction-coil so worked as to give freely sparks of 50 mm., and to reinforce it by a Leyden jar which reduces the length of these sparks to 5 mm.; it suffices for this to use a jar of 1 to 2 liters. The choice of metals for the points is equally important; zinc, aluminium, and especially magnesium give sparks that are very photogenic. These metals possess the disadvantage of oxidizing quite rapidly in air, so that it is necessary from time to time to clean the points with a file. The metallic sticks may have 5 mm. diameter, and the distance apart of the points is 2 mm. One might without doubt, using mercury,

which gives sparks as photogenic as does magnesium, construct an enclosed apparatus in which the metal would be preserved unchanged.

To produce the interruption there is attached to the pendulum (Fig. 42) a vertical platinum fork which dips into two cups of mercury covered with alcohol. It is useful, in order to reduce to a minimum the resistance that the immersion of the fork opposes to the motion of the pendulum, to place this fork in the same horizontal plane as the axis of rotation of the pendulum. In this way one avoids the translatory movements in the mercury which cause the most trouble.
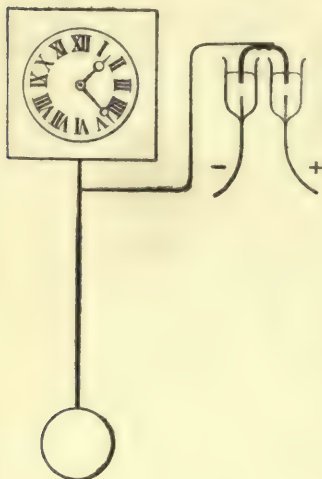
FIG. 42.

The only refinement with this intermittent lighting is to obtain, with a spark much too large and irregular to be photographed directly, the illumination of a very narrow slit. It is not sufficient to place the spark behind the slit and at a small distance away, because the slightest displacement of the spark would cause the luminous beam to fall outside of the mirror of the galvanometer. This difficulty
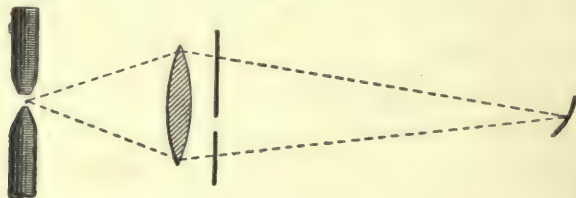
FIG. 43.

is overcome by a well-known artifice. A lens is placed between the electrodes and the mirror (Fig. 43); the posi-

tion of the electrodes is so adjusted that the image of the mirror is formed between them. With a distance apart of the electrodes of 2 mm., a lens of 100 mm. focal length and a mirror of 25 mm. diameter, the image of the latter will touch the two points; the spark then necessarily crosses the image of the mirror, and the radiations passed by the lens will fall certainly upon the mirror. One is thus sure in placing before the lens a fine metallic slit that all the rays transmitted will reach the mirror and will be sent to the photographic plate, and that whatever may be the position of the slit in front of the lens.

To save time it is advantageous to take several sets of observations on the same plate; this is easily done by arranging the plate so that it may be displaced vertically between two series, or in adjusting the slit so that it may be moved similarly before the lens.

The diagram (Fig. 44) is the reproduction of negatives
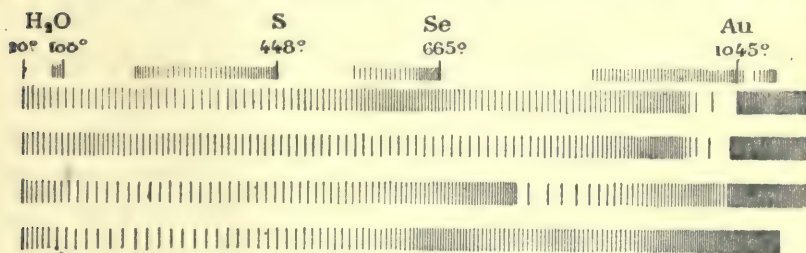
FIG. 44.

relative to the action of heat on clays. The first line gives the graduation of the couple; it has been drawn from several different photographs which have been grouped to economize space. The following lines are reproductions of negatives made in phototypography without any intervention of the hand of the engraver. The second line, for example, represents the heating of an ordinary clay. A slight contraction of the lines between 150° and 350° indicates a first phenomenon with absorption of heat;

it is the vaporization of the enclosed water. A second cooling much more marked between 550° and 650° shows the dehydration properly so called of the clay, the liberation of the two molecules of water in combination. Finally, the considerable spacing of the lines at 1000°. shows a sudden setting-free of heat corresponding to the isomeric change of state, after which the alumina becomes insoluble in acids. The other rows refer to the heating of other varieties of clay, the third row to kaolin, the fifth to steargilite.

Continuous Recording.—The continuous recording of temperatures is of much more general usage, even in scientific laboratories, by reason doubtless of the greater simplicity of its installation. It has been studied especially by Roberts Austin, director of the royal mint at London. A vertical slit lighted from a convenient source projects its image, by means of the galvanometer mirror, on a metallic plate pierced by a fine horizontal slit, and behind this slit moves a sensitive surface, plate or paper, which receives the luminous beam, defined by the intersection of the horizontal slit with the image of the vertical slit. If all were at rest, the impression produced by this luminous beam would be reduced to a point. If the plate alone is moved, a vertical straight line will be had; if the galvanometer mirror alone turns, a horizontal line. Finally, the simultaneous displacement of the plate and mirror gives a curve whose abscissas represent temperatures, and whose ordinates time. The illumination of the slit and the motion of the sensitive surface may be realized in many different ways.

Lighting of the Slit—There are two quite distinct cases to consider, that of laboratory researches by rapid heating or cooling, which last only a few minutes, and that of continuous recording of temperatures in industrial works,

which may last hours and days, that is to say, periods 100 times to 1000 times longer.   The rate of displacement of the sensitive surface, and consequently the time of exposure to the luminous action, may vary in the same ratio.   The luminous source necessary will be therefore quite different, depending upon the case.   For very slow displacements it is sufficient to use a small kerosene lamp with a flame of 5 to 10 mm. high.   For more rapid displacements use may be made of an ordinary oil-lamp, an Auer burner, or an incandescent lamp; finally, for very rapid displacements of the sensitive plate, 10 mm. to 100 mm. per minute, one may advantageously employ the oxyhydrogen flame or the electric arc.   For oxyhydrogen light the most convenient is the lamp of Dr. Roux with magnesium spheres; it consumes little gas and is enclosed in a metallic box which prevents all troublesome diffusions of the light.

The electric arc gives much more light than is needed, and the rapid wearing away of the carbon, by displacing the positions of the luminous point, renders difficult the permanence of suitable illumination of the slit.   For very short experiments one may very conveniently use the mercury-lamp in vacuo (Fig. 45) or the arc playing between two mercury surfaces.   In order to run it 3 amperes at 30 volts are requisite.   Its only disadvantage is to go out after running a few minutes on account of the evaporation of the mercury in the central tube.   It suffices, it is true, to give it a slight jar to make it go again, by causing a small quantity of mercury to pass from the outside annular space into the central tube.
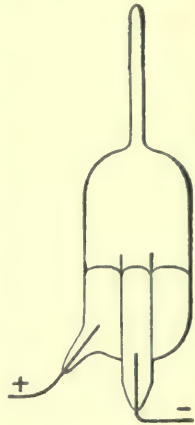
FIG. 45.

Whatever the luminous source employed, the slit may

be always lighted by means of a lens arranged as was indicated for discontinuous recording, that is, projecting upon the galvanometer mirror the image of the luminous source.   When this is large enough, it suffices to place the slit before the luminous source, bringing it up close enough so as to be sure that some of the luminous rays passing through fall upon the mirror.   But there is danger here of so heating considerably the slit that it may be altered; for this reason one is led to use more voluminous light-sources than would otherwise be necessary.   In the case of the use of a lens, the useful luminous intensity is as great as in placing the slit immediately next to the luminous source, so long as the image of the latter is greater than the galvanometer-mirror; now with the ordinary dimensions of the sources employed this condition is always fulfilled without any special precaution.

Instead of a slit lighted by a distinct luminous source, use may be made of a platinum wire, or better, as does Charpy, employ a carbon filament of an incandescent lamp heated by an electric current.

In order that the line traced by the recorder be very fine, it is necessary that the two slits, the luminous slit and the horizontal slit, be equally fine.   Skilful mechanicians can cut such slits in metals.   But it is easier to make them by taking a photographic plate of bromide-gelatine that has been exposed to the light, developing until completely black, then wash and dry.   By cutting the gelatine with the point of a penknife guided by a ruler, one may get transparent slits of a perfect fineness and sharpness.

Sensitive Surface.—For sensitive surfaces use is made of plates or films of bromide-gelatine.   Professor Roberts Austin employs exclusively plates which permit more easily the printing of a great number of positive proofs. Charpy, in his researches on the tempering of steel, made

use of sensitive paper, which permits a much more simple installation.

Paper.—For industrial recording, paper would allow of the employing large rolls lasting several days, as in the recording magnetic apparatus of Mascart. But in general one wants to have quickly the results of the record; this is always the case in laboratory investigations, and almost always in industrial studies. It is thus preferable to be content with quite short bands of paper rolled on a cylinder. There exists such a model quite well known and easy to use: the recording-cylinders with an interior clock-movement of the firm Richard. They may be ordered from the maker with any desired rate of rotation; unfortunately this rate cannot be changed at the pleasure of the operator, a desideratum in laboratory investigations.

Fig. 46 represents the installation of the recording-
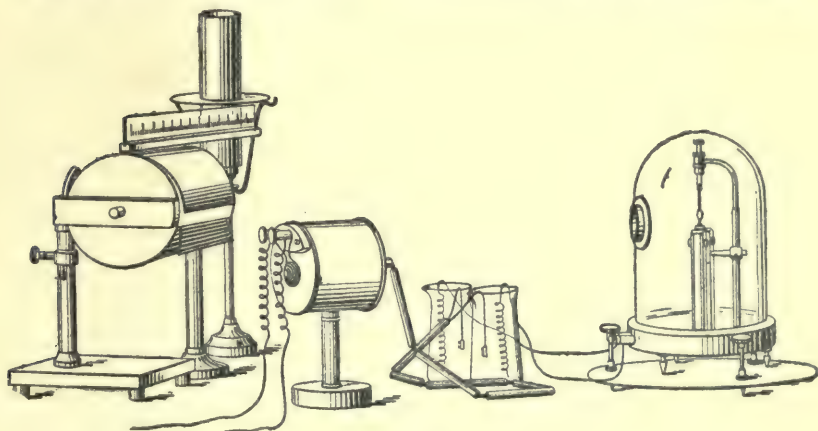
FIG. 46.

pyrometer used by Charpy in his researches on the tempering of steel. To the right the galvanometer, to the left the Richard recording-cylinder, and in the middle the electric furnace used for heating the samples of steel.

Plates.—The plate may be placed in a movable frame regulated by a clock-movement; this is the first arrangement employed by Prof. Roberts Austin (Fig. 47).　But
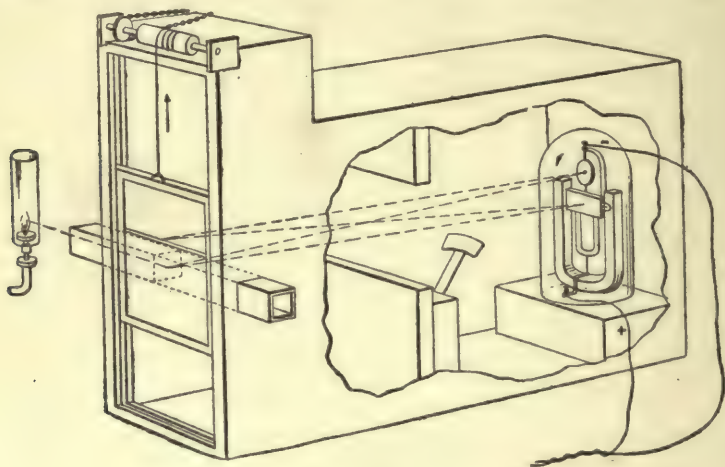
FIG. 47.

this installation, somewhat costly and complicated, has the same disadvantage as the recording-cylinders in that but a single speed can be given to the sensitive surface.
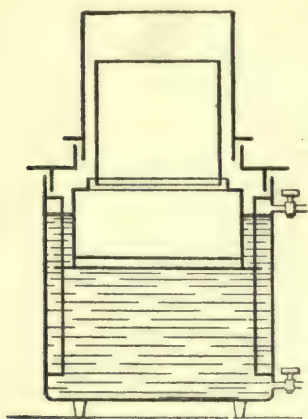
FIG. 48.

In order to drive the plate Roberts Austin now uses a buoyed system in which the rate of rise of level of the water is controlled at will by the agency of a Mariotte's flask and a simple watercock.　The plate is kept in an invariable vertical plane by means of two lateral cleats whose friction is negligible on account of the mobility of the float.　The sketch (Fig. 48) gives the arrangement of a similar apparatus made by Pellin for the laboratory of the Collège de France.

It carries a 13 × 18 cm. plate which is attached to the float by means of two lateral springs not shown in the sketch. Neither are the two guides of the float, immersed in water, indicated; the play next the cleats is only two-tenths of a millimeter. The uncertainty that this play can cause in the position of the plate is quite negligible. The curve (Fig. 49) is the reproduction of an experiment made with such an arrangement by Roberts Austin on the solidification of gold.
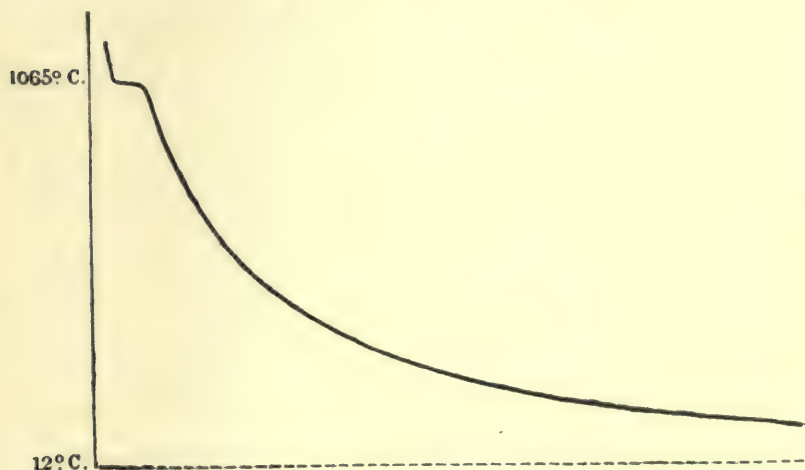
FIG. 49.

During the whole period of freezing, the temperature remained stationary, then lowering of temperature was produced at a regularly decreasing rate as the temperature of the metal approached that of the surroundings.

It is indispensable to trace on each sensitive surface on which is to be recorded a curve, the line corresponding to the surrounding temperature, or at least a parallel reference line. This is very easy in the case of the guided plate or of the paper rolled on a cylinder. It suffices, after having brought the couple to the temperature of its surroundings, to displace in the opposite direction the

sensitive surface; the second curve traced during this
inverse movement is precisely the line of the zero of the
graduation of the temperatures. But this is a dependence
that may be evaded by registering at the same time as the
curve a reference line by means of a fixed mirror attached
to the galvanometer in the path of the luminous beam
which lights the movable mirror. Roberts Austin likewise
makes use of the luminous beam reflected by the fixed
mirror to inscribe the time in a precise manner. A
movable screen driven by a seconds pendulum cuts off at
equal intervals of time this second luminous beam. The
reference line, instead of being continuous, is made up of
a series of discontinuous marks whose successively corre-
sponding parts are at intervals of one second as is shown
in Fig. 49.

The curves once obtained must be very carefully ex-
amined to recognize the points where the gradient presents
slight anomalies, characteristic of the transformations of
the body studied. Generally these irregularities are
very insignificant, and it would be well, in order to
recognize them with certainty, to obtain curves traced on
a much greater scale. Practically this magnification is
not possible; one may increase the sensitiveness of the
galvanometer, and thus the deflection, but then for the
greater range of temperature the luminous image would
fall off the sensitive plate. Prof. Roberts Austin has over-
come this difficulty in an ingenious manner. He no longer
registers the temperature of the body, but the difference
between this temperature and that of a neighboring body
which presents no transformation, platinum for instance.
This difference of temperature, always small, may be
recorded by a very sensitive galvanometer. If, at a given
moment, the body, other than the platinum, undergoes a
change of state accompanied by heat phenomena even very

weak, the difference of the two temperatures, by reason of
its small value, will undergo variations relatively very
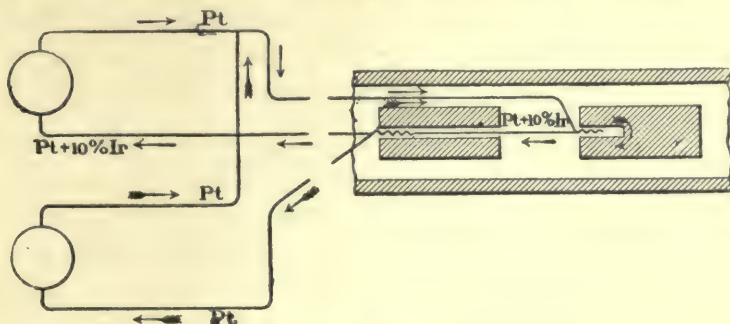
FIG. 50.

great. If it is desired not merely to recognize the exist-
ence of a phenomenon, but besides to measure the tem-
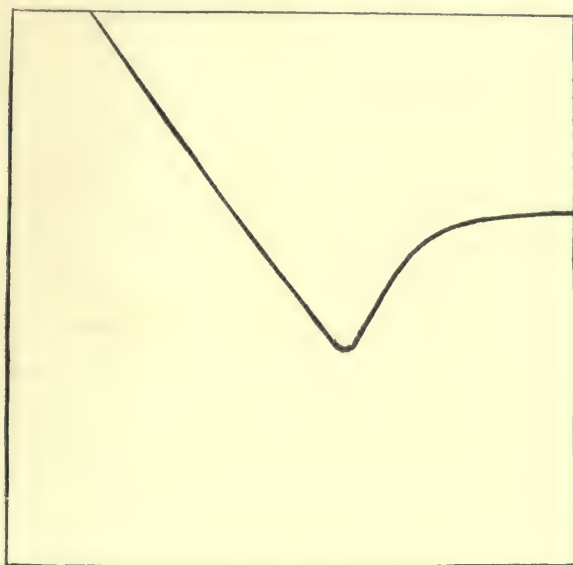
FIG. 51.

perature at which it is produced, it is necessary to employ
simultaneously a couple connected to another galvanom-
eter. With three leads, two of platinum and one of
platinum-rhodium, a complex couple may be made, giving

simultaneously the actual temperatures and the differences of temperature of two neighboring bodies. The diagram (Fig. 50) gives an idea of this arrangement which has proved very useful in the hands of Roberts Austin for the study of alloys, and particularly for the study of the transformations of irons and steels. The curve of the solidification of tin is reproduced in Fig. 51, as obtained by this method. The double inflection indicates the existence of marked under-cooling; the tin, before freezing, is lowered to 2° below its fusing-point, to which it returns suddenly as soon as solidification sets in.

Recording-pyrometers have been for the most part employed up to the present only in scientific laboratories. There exist, however, a few in metallurgical works, as the blast-furnaces at Clarence Works of Sir Lothian Bell and the blast-furnaces of Dowlais. The curves of Fig. 52 give
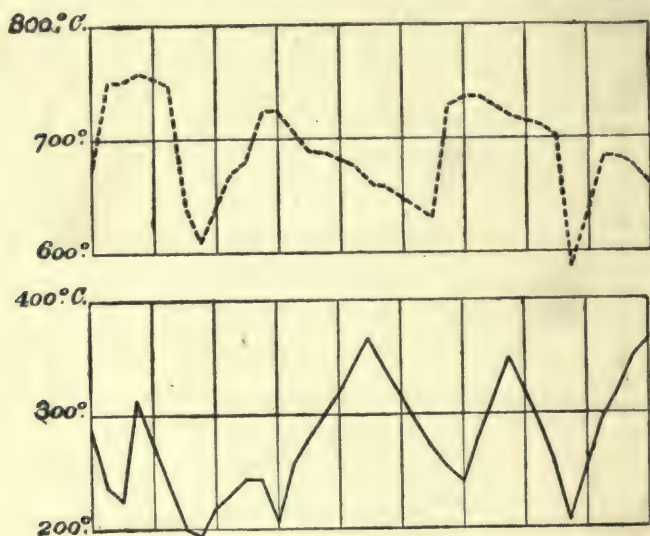
FIG. 52.

an example of the curves obtained at Clarence Works; the lower curve gives the temperature of the gas at the furnace-mouth, and the upper curve that of the hot blast.

CHAPTER XII.

CONCLUSION.

In closing this account it will not be useless to call the attention of investigators to points whose study seems the most needed to aid the progress of our knowledge of high temperatures. We will mention first the precise determination of the fixed points serving for the graduation of pyrometers; there does not exist at the present time above the boiling-point of sulphur any temperature known certainly to 1°. For the ebullition of zinc, the fusing of silver and that of gold, which are at present the best known, the uncertainty may be 10°. It would be well also to try and find substances serving for fixed points that are more convenient to handle than the metals—salts, for example—which do not attack platinum either when they are melted or when they are vaporized; these substances should be found easily and economically in a state of purity; they should possess well-defined points of fusion and of ebullition, which is not always the case when the crystallized salt has several dimorphous varieties.

A second very important point for investigations of great precision would be the determination of the general form of the function which connects electrical resistance with temperature. One cannot hope to determine completely this function with the value of its parameters, because there are not two samples of platinum having

exactly the same resistance; it is necessary in each case to make the calibration by means of fixed fusing- or boiling-points. The number of such points to compare depends on the number of parameters contained in the formula. By his researches in this matter, Prof. Silas Holman has greatly facilitated the use of thermoelectric couples by showing that it is sufficient between 0° and 1800° to use a logarithmic formula containing only two parameters.

For the measurement of exceedingly high temperatures which can be effected only by methods employing radiation, and depending upon extrapolations often considerable, it would be very useful to determine with greater precision, than has been done as yet, the law of the radiation from a rigorously black body (enclosed space), either for a monochromatic radiation, as radiation transmitted by the red glasses, or for the totality of heat radiations. But such a study can be of value only on the condition of possessing a very great precision, difficult to attain actually on account of the uncertainty which still exists as to the temperatures directly measurable. For a moderate precision the formulæ of Stefan and of Le Chatelier will do, as they are certainly very near to the truth, since they are sensibly in agreement up to the temperature of the sun, about 8000°. It will certainly be necessary to verify and determine more accurately the parameters which enter into these two formulæ.

In closing we beg to call attention to a fact of some importance. The measurement of high temperatures possesses certainly great interest from the point of view of the progress of pure science; but it is to be noted that industrial needs have stimulated the partial solution of this problem: Wedgwood, the china manufacturer, seeking to better his processes; similarly, Leger, at the Berlin works,

occupied himself exclusively with ceramic products; Siemens sought to regulate the making of steel; the engineers of the Paris Gas Company wanted a means of control over the distillation of oil; Le Chatelier studied the thermoelectric pyrometer in the course of investigations on the baking of clay and on the manufacture of cements; he studied the optical pyrometer at the request of a Sheffield steel manufacturer, Hadfield, who desired for his works a pyrometer uniting accuracy with simplicity of use. Roberts-Austen, director of the mint at London, has devoted all his efforts for many years past to the study of industrial alloys, obtaining results of great value, largely due to the utility of the recording-pyrometer.

This incentive of practical needs on the progress of science is not surprising. The savants who founded chemistry recognized no distinction between pure and applied science. Lavoisier, Chevreul, Gay-Lussac, Dumas, Thénaud, H. Sainte-Claire-Deville went indifferently into the laboratory or the works. It is the present trend of our teaching methods that has opened a breach increasing in size every day between theory and practice.

In the scientific laboratories all efforts follow in well-beaten paths. There one is free to choose his subjects of study according to his caprices; one may be easily guided by artificial preoccupations, concerning themselves but very indirectly with a study of nature. Finally, one may have confidence for a long time in erroneous results without having any inkling of the error committed. In industrial works it is quite otherwise: one cannot remain stationary upon problems already solved; in spite of one's self one must march ahead. Subjects of study obtrude and must necessarily be taken up in the order of their real importance. Wrong conclusions are made evident by their contradictions at each instant with facts that one cannot

refuse to see.   These conditions explain how laboratories attached to industrial works, with their insufficient personnel absorbed largely in other matters, with their rudimentary material, come nevertheless to contribute largely to the progress of pure science.   All the progress so important in the chemistry of iron is made to-day in industrial works and in the laboratories attached to them.

It is not in chemistry alone that practical needs have manifested this creative power.   It was in studying the boring of cannon that Rumford met the notion of the conservation of energy; it was in reflecting upon the steam-engine that Sadi-Carnot established the basis of thermodynamics; it was in seeking to perfect light-house lenses that led Fresnel to his investigations on the theory of light.

CHAPTER XIII.*

RECENT DEVELOPMENTS.

As several important pyrometric investigations have been finished the past year, since the appearance of the French edition of this work, it may not be out of place to call attention to some of the advances that have been made.

Gas-pyrometry.—It is now generally agreed that for temperatures above 200° C. it is advisable to use nitrogen as the thermometric substance. Hence a knowledge of the behavior of this gas is of prime importance. Chappuis and Harker, working at the International Bureau at Sèvres, have investigated anew the relation between the thermometric scale of the nitrogen-thermometer at constant volume, under an initial pressure of 800 mm., and the normal scale of temperatures from 0° to 500°. The expression for the dilatation of nitrogen at $t°$ deduced from observations with their thermometer, under a pressure of 1 meter of mercury at 0° C., is

$$\beta = 0.00367698 - 7.826746.10^{-8} . t + 4.78007610^{-10} . t^2,$$

and their observations indicate the existence of a limiting value of this coefficient (i.e., supposing nitrogen to rest a perfect gas to 0° abs.)

$$\beta_{\text{lim.}} = 0.00367380,$$

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* Written by the translator.

and as the mean coefficient of dilatation between 0° and 100°

$$\beta_{0-100} = 0.00367466.$$

The divergences of the nitrogen-thermometer from the normal scale were found to be as follows:

Temperatures.	Differences of Scale. Actual Scale—Normal Scale. $P_0 = 1$ meter.
100°	0°.000
150	−0 .008
200	−0 .017
250	−0 .026
300	−0 .034
350	−0 .043
400	−0 .051
450	−0 .060
500	−0 .068

Thus up to 500° C. the divergence of the nitrogen constant-volume scale from the normal scale is very slight, and appears to be of less account than other sources of uncertainty. This divergence is further lessened with smaller values of the initial pressure (P_0); and is less than 0°.04 at the sulphur boiling-point, for a value of $P_0 = 550$ mm.

The divergence of the nitrogen constant-volume thermometer from the normal scale of temperatures in terms of the initial pressure leads to the expression

$$\frac{\delta \beta}{\delta p} = 1.32 . 10^{-8} \text{ per mm. change of pressure.}$$

For very low initial pressure this gives

$$\beta_{\text{lim.}} = 0.0036613.$$

For hydrogen: $\left\{ \begin{array}{l} \alpha_{\text{lim.}} = 0.0036625 \\ \beta_{\text{lim.}} = 0.0036624 \end{array} \right\}$ according to Berthelot.

For *high* temperatures the constant-pressure form is probably more accurate and convenient (Barus, Chappuis,

Callendar). For nitrogen under constant pressure Chappuis gives

$$\frac{\delta \alpha}{\delta p} = 1.19 \cdot 10^{-3} \text{ per mm.}$$

and

$$\alpha_{\text{lim.}} = 0.0036612.$$

The divergences from the normal scale in this case are about double those at constant volume.

Callendar suggests that probably helium will eventually be used in defining the normal scale of temperatures.

An extended study of the constant-volume thermometer has been made by Holborn and Day at the Reichsanstalt, Berlin. They find that for work up to 500° C. a more suitable substance for the thermometer-bulb than porcelain is a hard borosilicate glass, Jena 59$^{\text{III}}$; that porcelain should not be used at all; and that for temperatures above 500° a platin-iridium bulb filled with pure nitrogen at an initially low pressure gives entirely satisfactory results and is easy to handle. A great improvement over the older methods of heating for all temperatures is the use of an electric oven made of nickel wire wound upon a thin tube of porcelain or clay and suitably enclosed. Their form of gas-thermometer is almost identical with that of Chappuis.

They determined also, among others, the following expansion coefficients per unit length at 0°:

Jena 59$^{\text{III}}$: $\lambda = 18.10^{-6}$ ....from 0°–100°
Porcelain   : $\lambda = (2954t + 1.125t^2)10^{-9}$ ....from 0°–1000°
Platinum   : $\lambda = (8868t + 1.324t^2)10^{-9}$ ....from 0°–1000°
Palladium   : $\lambda = (8198t + 1.418t^2)10^{-9}$ ....from 0°–1000°
Silver   : $\lambda = (18270t + 4.793t^2)10^{-9}$ ....from 0°–875°
Nickel   : $\lambda = (13460t + 3.315t^2)10^{-9}$ ....from 300°–1000°
Pt—10% Ir : $\lambda = (8889t + 1.274t^2)10^{-9}$ . ...from 0°–1000°
Pt—20% Ir : $\lambda = (8198t + 1.418t^2)10^{-9}$ ....from 0°–1000°

Regarding the absolute value of temperatures as deduced by comparison with the gas-pyrometer, the following quotation from Barus * is to the point:

"If, as is undoubtedly true, platinum is impermeable to nitrogen at dull-red heat and at white heat, we witness finally the solution so long deferred of the pyrometric problem, at least for the lower region of high temperatures. We are grateful to our predecessors for the data they have left us, but it is expedient to lay aside all their work and to endeavor to obtain entirely new results by means of new apparatus clearly freed from systematic errors. The Reichsanstalt is to be congratulated for having taken the first step in this direction."

Thermoelectric Pyrometer. — As the thermoelectric couple has come into such general use, the importance of ready and accurate calibration is apparent. If the couple is to be used over only a short range of temperature, interpolation in the Avernarius formula

$$\Sigma_0^t e = at + bt^2$$

is sufficient, the determinations of two known fixed points being required. For more extended ranges of temperature this formula may be replaced to advantage by the Holman logarithmic formula:

$$\Sigma_0^t e = mt^n.$$

The two constants are readily computed or evaluated graphically, and the resulting plot serves indefinitely for the determination of any temperature with a given couple. The equation loses in precision below 250° C. It may be written

$$\log \Sigma_0^t e = n \log t + \log m,$$

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* Tr. of Report to Physics Congress, Paris, 1900.

and if log $\Sigma_0^t e$ is plotted as abscissas and log t as ordinates, the resulting curve is a straight line. Unfortunately, in the experimental work of Holman, Lawrence and Barr, they assumed the value of the melting-point of gold as 1072° (Holborn and Wien). Taking the now best-known value of this point, 1064° (Holborn and Day, D. Berthelot), and for the boiling-point of sulphur 445°, the application of this formula gives the following values of the melting-points that they determined:

Al	Ag	Au	Cu	Pt
654.7	962.7	[1064]	1087	1760

If we compare these values with those recently obtained by Holborn and Day at the Reichsanstalt:

Al	Ag	Au	Cu
* 657.3	961.5	1064	1084

made by means of a thermo-couple in direct comparison with the gas-thermometer, and bearing in mind that Holman did not use an electric heater, we see that his formula may be applied in all confidence to the determination of high temperatures in ordinary practice. For the calibration of the couple, the boiling-point of sulphur (445°) and the melting-point of copper (1064°.9 in an oxidizing atmosphere or 1084°.1 in a reducing atmosphere) are amply sufficient and easily obtained.

For an accuracy of $\pm 1°$ C., Holborn and Day have shown that above 250° C. the following formula holds within wide limits:

$$\Sigma_0^t e = -a + bt + ct^2,$$

and they have employed it in their recent researches. The labor involved in computation with this form is considerable, and unless a very great accuracy is required

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* For measurements in a graphite crucible a slightly lower value was found.

Holman's formula is amply sufficient, when the uncertainty of the absolute values of high temperatures is considered.

Stansfield deduces from theoretical considerations the formula

$$T\frac{dE}{dT} = aT + b,$$

which may be written

$$E = aT + b \log T + c,$$

a form which satisfies the experimental results determined with pure platinum wires. This form possesses no practical advantage over that of Holborn and Day, unless it be its usefulness, by employing the graphical method, in detecting slight errors in fusing-points. The values of $\frac{dE}{dT}$ at the points of fusion can be obtained from the T *vs.* E plot, and the T *vs.* $\frac{dE}{dT}$ curve thus constructed throws into prominence the experimental errors at these points. As the above formulæ indicate, the curve for the platinum metals constructed with T as abscissas and $T.\frac{dE}{dT}$ as ordinates is a straight line. The errors of the method are less than 2° at 1000°. The ordinary metals, on the other hand, give nearly a straight line for the curve T *vs.* $\frac{dE}{dT}$.

Stansfield worked with Austen's recording-pyrometer, which he has rendered still more sensitive by means of an auxiliary potentiometer, which balances the major part of the E. M. F. of the couple, the sensitive galvanometer being acted upon by only a small fraction of the thermo-current. The "cold" junction was kept in boiling water. He obtained the following fixed points:

Zinc	Aluminium	Silver	Gold	Copper
418°.2	649°.2	961°.5	1062°.7	1083°.0

After having calibrated several couples with their new platinum gas-pyrometer, Holborn and Day determined a series of boiling- and fusing-points of certain metals and alloys, obtaining very concordant results:

Cadmium.....	321°.7 ± 0°.1	(From 10 observations on two days.)
Lead.........	326 .9 ± 0 .2	" " " " " "
Zinc........	419 .9 ± 0 .2	
Antimony.....	630 .5 ± 0 .3	
Aluminium...	657 .5 ± 0 .5	(In a graphite crucible, a lower value.)
Silver.......	961 .5 ± 0 .9	(Pure; i.e., in reducing atmosphere.)
Silver...	955	(In air; point ill defined.)
Gold (samp. 1)	1064 .0 ± 0 .6	
Gold (samp. 2)	1063 .5	(Crucible method.)
Gold (samp. 2)	1063 .9	(Wire method.)
Copper........	1064 .9	(In air.)
Copper........	1084	(Pure.)

Their "wire method" is to insert into the circuit at the hot junction a centimeter of the wire whose melting-point is to be determined, and to note the E.M.F. at the instant the circuit breaks, due to the fusing of this wire. Only 0.03 gr. of gold are necessary to take an observation for that metal. As is evident from the table, the wire and crucible methods give identical results. The crucible may be of porcelain or graphite.

From a consideration of the work of Holborn, Stansfield, and Holman it is evident that, working under most diverse experimental conditions with different thermo-couples of pure metals, results are obtained agreeing to 0.5 per cent or even closer. The work of Holborn and Day practically makes the thermo-element independent of the gas-thermometer, for platinum can be obtained to-day in a state of great homogeneity and purity, giving always the same E.M.F. at the same temperature, unless having been exposed to furnace-gases at temperatures above 1200°; and there are a number of "fixed points" known to 0.2 per

cent within the range 200° to 1400°. In work of con-
siderable precision it is well to have at least two thermo-
elements, one being kept as a standard, heated only in
porcelain tubes and never higher than 1200° C.

If the platinum of the couple has become unhomo-
geneous by excessive heating and the E. M. F. thus changed,
the couple may be restored very nearly to its original con-
dition and E. M. F. by heating to white heat for some time
by the passage of a current (Holborn and Day) or by
heating the wire wound on a refractory-earth cylinder
(Barus).

Platinum-resistance Pyrometer.—For the exact deter-
mination of temperatures from the lowest to 700° or 800°,
this pyrometer gives by far the most accurate results,
whether it be a question of measuring a long range of
temperature or controlling the constancy of a temperature.
It is currently in use in England to measure temperatures
above 1000° where great accuracy is desired, but without
warrant, for the recent researches of Tory only emphasize
those of Holborn and Wien that even pure platinum
changes considerably its "zero" by uncertain amounts
when heated to 1000°, whether annealed or not, even when
care is taken to shield the metal.

To determine a temperature by means of a platinum-
thermometer it is necessary to know the "difference
coefficient," d, of the wire; or the difference between the
"platinum temperature" of the given wire and that of a
standard at any known temperature, as the sulphur boiling-
point or the silver freezing-point.

Callendar has suggested the following notation which
has come pretty generally into use:

Fundamental Interval = the denominator $R' - R^0$ in
the formula

$$pt = 100(R - R^0)/(R' - R^0), \quad . \quad . \quad . \quad (1)$$

for the platinum temperature pt, represents the change of resistance of the thermometer between 0° and 100°.

Fundamental Coefficient $= c =$ mean value of temperature coefficient of change of resistance between 0° and 100°:

$$c = (R' - R^0)/100 \ R^0.$$

Fundamental Zero $= pt^0 = \dfrac{1}{c} =$ reciprocal of fundamental coefficient. It represents the temperature on the scale of the instrument itself at which its resistance would vanish.

Difference Formula.—The following form is the most convenient for computation:

$$D = t - pt = d \cdot (t/100 - 1) \cdot t/100. \quad . \quad . \quad (2)$$

Parabolic Function expresses the vanishing at 0° and 100° of above formula, which becomes

$$t = pt + d \cdot p(t).$$

"S.B.P." Method of Reduction.—D is obtained very conveniently by determining R'', and thus pt'' at $t'' =$ the boiling-point of sulphur.

Resistance Formula.—The parabolic difference formula is equivalent to assuming

$$R/R^0 = 1 + at + bt^2, \quad . \quad . \quad . \quad . \quad (3)$$

where

$$a = c(1 + d/100), \quad b = -cd/10000.$$

Graphic Method of Reduction.—The easiest way to reduce platinum temperatures to the gas scale is to plot the difference $t - pt$ in terms of t as abscissas, and to deduce graphically the curve of difference in terms of pt as abscissas. This is most convenient for a single instrument up to 500°.

Other methods have been used by Heycock and Neville and by Tory.

Difference Formula in Terms of pt :

$$t - pt = d'(pt/100^{-1})pt/100 = d'p(pt). \quad . \quad (4)$$

This formula is to be used only where a high degree of accuracy is not required. The value of d' may be determined from S. B. P., or approximately

$$d' = d/(1 - 0.077d).$$

Dickson has proposed the formula

$$(R + a)^2 = p(t + b),$$

which agrees with (3) over a very wide range in the case of platinum. It has the possible theoretical advantage of not requiring a maximum value for the resistance of platinum. This form, however, does not lend itself to the convenient graphical treatment applicable to the difference formula.

There is advantage in using the silver fusing-point in calculating the value d for impure wires that are to be used at high temperatures. For the whole range of temperatures with such a wire both the sulphur and silver points may be obtained, when d takes the form $a + bt$.

The platinum-thermometer may be, and should be, constructed so as to read directly in platinum degrees. This method saves much time and chance of error. The calibration curve once made for a given instrument serves indefinitely, so that, in spite of the appearance of complications in the method, actually in practical use the determination of a temperature on the normal scale by the platinum-thermometer is the affair of a few seconds only. " With regard to portability and ease of reproduction, it is sufficient to send a few grammes of the standard wire in

an ordinary letter, to reproduce the scale with the utmost accuracy in any part of the world."

Chappuis and Harker have redetermined the sulphur boiling-point with a platinum-thermometer compared with the nitrogen-thermometer at the International Bureau at Sèvres. Their result is 445°.2, as compared with Callendar and Griffiths' value, 444°.53, determined some years ago. Besides the reasons given by Chappuis (difference in coefficient of bulbs, etc.), cumulative evidence seems to indicate that 444°.53 is too low a value for this point. For instance, assuming this value, the platinum-thermometer gives 1061° as the fusing-point of gold. The best determinations made independently of the sulphur point, Holborn and Day, and D. Berthelot, both give 1064° for the gold point. If the boiling-point of sulphur be 445°.0, then the platinum-thermometer also gives 1064° as the gold fusing-point.

The change in S.B.P. suggested by Chappuis corresponds to a change in d of the difference formula from 1.500 to 1.538.

Callendar has strongly urged the adoption of the platinum-pyrometer as a practical or secondary standard to be used independently of the air-thermometer by comparing all platinum-thermometers to one selected as standard, assuming values of the sulphur and silver points, 444°.5 and 962° respectively.

Fixed Points.—In the following table are grouped the most reliable recent determinations of the fixed points that may be used to advantage in pyrometry. Those put in brackets are the least exactly known or are difficult to determine experimentally.

Radiation Pyrometers.—In Germany at the present time very extensive researches are being carried on to determine and verify the laws of radiation, especially of

TABLE OF FIXED POINTS.

Author.....	Holman, etc. (corr. by G.K.B.) 1896	D. Berthelot 1898–1901	Heycock & Neville, Callendar 1895–99	Stansfield 1898	Holborn & Day 1900–1901
Date.......					
Instrument.	Thermo-couple	Optical Interference	Electrical Resistance	Recording Thermo-couple	Thermo-couple and Nitrogen-ther.
Calibration data	445°.0 / 1064	Expansion of air	0° / 100° / 444°.53	0° / 100° / 444°.53	Platinum-bulb Nitrogen-ther.
Sn...........			231°.9	232°.1	
Bi...........			269.2	268.4	
Cd...........			320.7		321°.7
[Pb].........			327.7	325.9	326.9
Zn...........			419.0	418.2	419.0
Sb...........			629.5		630.6
[Cd].........		778°			
[Al].........	654°.7		645.5	649.2	657
[Zn].........		918			
[Ag (in air)].					955
Ag (pure)...	962.7	962	960.7	961.5	961.5
Au	(1064)	1064	1061.7	1062.7	1064.0
Cu (in air)...					1064.9
Cu (pure)....	1087		1080.5	1083.0	1084.1

black bodies at high temperatures. Although no new form or modification of radiation pyrometer' has as yet been introduced as a consequence of these measurements, the work being done and already accomplished will eventually in all probability form the basis for the determination of very high temperatures, use being made of an instrument of the bolometer type receiving radiation from a surface of known emissive properties.

The first of these laws, established experimentally by Stefan in 1879 in a not entirely satisfactory manner, and since deduced theoretically from thermodynamic considerations by Boltzmann, and from the electromagnetic theory by Planck, and further confirmed with certain limitations by numerous observers, states that the total radiation of a body is proportional to the fourth power of the absolute temperature, or

$$S = \int_0^\infty E d\lambda = c \cdot T^4, \quad . \quad . \quad . \quad . \quad (1)$$

where S is the total radiant energy at any absolute temperature T, $E d\lambda$ is the energy radiated in waves of length $< \lambda + d\lambda$ and $> \lambda$, and c is a constant.

The following table indicates the limits within which (1) holds. The results are those of Lummer and Pringsheim, obtained with various radiating substances and a strip-bolometer. The temperatures are expressed in terms of Holborn and Day's platinum-bulb nitrogen-thermometer as compared with a thermo-element.

Nos. 5, 8, and 9 probably owe their divergences to the fact that they were obtained with a Perrot furnace at low temperatures and heat equilibrium was not realized.

From the table it is evident that (1) is satisfied between the temperatures of 100° and 1300° C.

Nos.	$c \cdot 10^{10}$	Absolute Temperature.	Calculated Temperature.	T obs.—T cal.
1	127	373°.1	374°.6	− 1°.5
2	124	492 .5	492 .0	+ 0 .5
3	124.8	723	724 .3	− 1 .3
4	126.6	745	749 .1	− 4 .1
5	(116.7)	789	778 .0	+11 .0
6	121.6	810	806 .5	+ 3 .5
7	123.3	868	867 .1	+ 0 .9
8	(115.9)	1092	1074	+18
9	(116.3)	1112	1095	+17
10	124.2	1378	1379	− 1
11	123.1	1470	1468	+ 2
12	120.9	1497	1488	+ 9
13	122.3	1535	1531	+ 4

Mean.... 123.8

Assuming Stefan's law to be true, Wien and later Thiessen and Planck developed theoretically the expression

$$\lambda \cdot T = \text{const.}, \quad \ldots \quad (2)$$

from which follow

$$\lambda_m \cdot T = \text{const.} = A, \quad \ldots \quad (3)$$

$$E_m \cdot T^{-5} = \text{const.} = B, \quad \ldots \quad (4)$$

where λ_m is wave-length of maximum energy at temperature T, and E_m is the energy of λ_m.

The following confirmation of (3) and (4) was obtained by Lummer and Pringsheim:

λ_m	E_m	$A = \lambda_m T$	$B = E_m \cdot T^{-5}$	Absolute Temperature.	$T = \sqrt[5]{\dfrac{E_m}{B_{\text{mean}}}}$.	Diff.
4.53	2.026	2814	2190.10^{-17}	621°.2	621°.3	+ 0°.1
4.08	4.28	2950	2166	723	721 .5	− 1 .5
3.28	13.66	2980	2208	908 .5	910 .1	+ 1 .6
2.96	21.50	2956	2166	998 .5	996 .5	− 2 .0
2.71	34.0	2966	2164	1094 .5	1092 .3	− 2 .2
2.35	68.8	2959	2176	1259 .0	1257 .5	− 1 .5
2.04	145.0	2979	2184	1460 .4	1460 .0	− 0 .4
1.78	270.6	2928	2246	1646	1653 .5	+ 7 .5

Mean.... 2940 2188.10^{-17}

The small differences among the values of A are within the limits of precision with which it is possible to determine λ_m. The agreement among the values of B, which depend on the fifth power of T, is very satisfactory, bearing in mind also that above 1000° the temperature is determined by extrapolation in Holborn and Day's formula.

Two other series of observations, with different arrangement of apparatus in each case, gave values for A of 2940 and 2930, and equally satisfactory constancy for B.

Paschen has also made a long series of careful investigations on this matter. He makes use of two methods: one, measurements on cavities of various kinds with heated walls; and the other, of the radiation of the black body by the method of reflection. The mean of his latest results for A reduced to Holborn and Day's scale is 2920 with a mean error of 16. Wanner also obtains $A = 2920$.

Wien also deduced as the expression for the total energy of radiation of a black body

$$E = C\lambda^{-5}e^{-\frac{c}{\lambda T}}. \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (5)$$

C and c are determined from A and B of (3) and (4).

A slightly modified form, due to Planck:

$$E = C\lambda^{-5}\frac{1}{e^{\frac{c}{\lambda T}} - 1}, \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (6)$$

is found by Paschen to hold more generally than does the Wien energy formula.

For very long waves these formulæ apply with less exactness, and also at high temperatures the value of A is slightly higher than at low temperatures, according to Paschen.

For most substances heated to incandescence the value of $\lambda_m T$ is on the average 2630, instead of 2930 as in the case of a " black " body. Therefore, without knowing the

"blackness" of the surface in question, its temperature may be approximately found as being surely between two well-defined limits, when λ_m is known for the body. In the formula

$$E = C\lambda^{-a} e^{-\frac{c}{\lambda T}}$$

$\alpha = 6$ for platinum and $\alpha = 5$ for a black body, and in general it is safe to take $6 > \alpha > 5$.

Lummer gives the following values calculated in this way, supposing the bodies to be "platinum-black":

	λ_m	$T_{\text{max.}}$	$T_{\text{min.}}$
Electric arc..............	0.7μ	4200° abs.	3750° abs.
Nernst's lamp.............	1.2	2450	2200
Auer burner....	1.2	2450	2200
Incandescent lamp......... ...	1.4	2100	1875
Candle....................	1.5	1960	1750
Argand burner........ ,...	1.55	1900	1700

Other Pyrometers. — Mercury in glass thermometers reading up to 575° are now obtainable. The glass is Jena 59[III] or a similar hard one, and the instrument is filled under great pressure, nitrogen usually occupying the stem above the mercury. A vacuum jacket sometimes surrounds the upper part of the stem to eliminate uncertain stem-exposure corrections.

Dufour has succeeded in constructing a tin in quarz pyrometer permitting measurements from 240° to considerably above 1000°. If such pyrometers could be made commercially they would be useful, as such an instrument has no zero lag and is direct-reading.

Wiborgh of Stockholm has on the market a "thermophone" suitable for the discontinuous determination of temperatures. It consists of a cylinder of refractory earth, 2.5 cm. long and 2 cm. in diameter, containing an explosive. The thermophone is deposited in the region whose temperature is to be ascertained, and the time is

noted to one-fifth second until the cylinder explodes. A table then gives the required temperature. Different cylinders of the same set agree to one-fifth second, or 20° at 1000°. These thermophones are more convenient than, and as cheap and accurate, as, the Seger cones.

Conclusion.*—The actual state of pyrometry is most encouraging. It is clear that in a few years from now pyrometry will be in possession of a series of constants as exact as those of the best developed branches of Physics. In Germany, a gas-thermometer impermeable to the thermometric gas and rigid up to white heat has been found, thanks to the efforts of Holborn, Wien, and Day, at the Reichsanstalt. In England, the efforts of Callendar, Griffiths, and others to construct an instrument of remarkable sensibility from the absolute zero to 1000° C. have been crowned with merited success.

In France, the best practical pyrometer has been found by Le Chatelier, and D. Berthelot has devised an optical method for the measurement of temperatures in absolute value, independent of the form and size of the thermometric envelopes, and whose upper limit is indefinite; for since we have learned, thanks to the great discovery of Nernst, that the refractory earths become conductors at high temperatures, it has become possible to heat electrically the most infusible substances up to the highest degrees on the scale.

With a thermostat of this kind, Berthelot's pyrometric method in absolute value marches side by side with the most advanced practical progress realized by Moissan; in other terms, pyrometry in absolute value is only limited to-day by the difficulty of the manufacture of apparatus in refractory materials.

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* Barus: Report to Physics Congress, Paris, 1900.
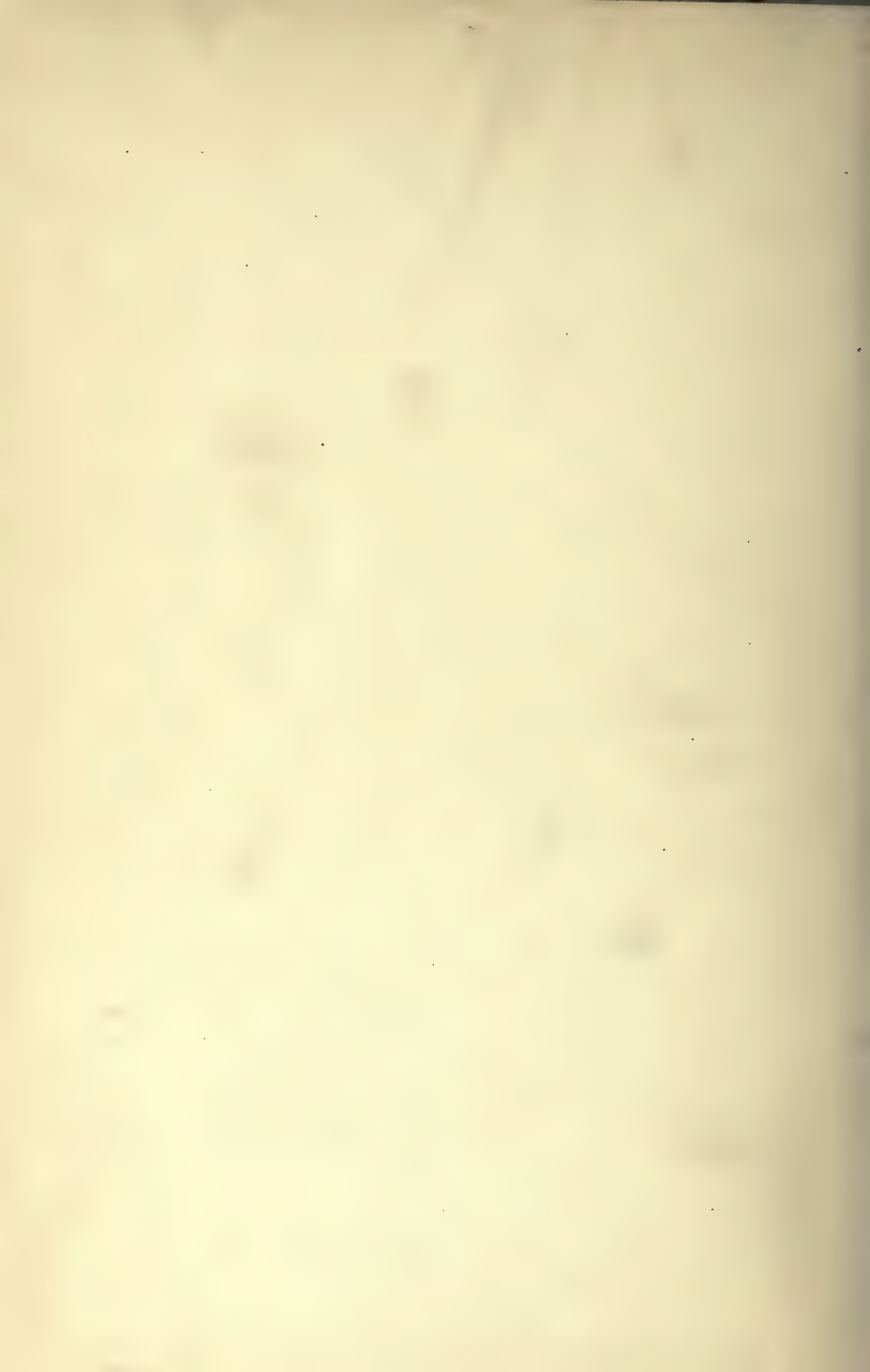
BIBLIOGRAPHICAL INDEX.

(The italic figures refer to volumes.)

NORMAL SCALE OF TEMPERATURES.

Carnot.—Reflections on the motive power of fire.

Lippmann.—Thermodynamics, p. 51.

Thomson and Joule.—Philosophical Transactions of the Royal Society, *42* (1862), p. 579.

Lehrfeldt.—Philosophical Magazine, *45* (1898), p. 363.

Callendar.—Phil. Trans., *178* (1888), pp. 161-220.

Regnault.—Account of his investigations, *1* (1847), p. 168.

Chappuis.—Studies of the gas-thermometer. Trav. du Bureau International des Poids et Mesures, *6* (1888).

Chappuis and Harker.—Trav. et Mem. du Bureau Int. des Poids et Mesures, 1900. Phil. Trans., 1900.

Schreber.—Absolute Temperature. W. Beibl., *22* (1898), p. 297.

GAS-PYROMETERS.

Prinsep.—Ann. Chim. et Phys., 2d Series, *41* (1829), p. 247.

Pouillet.—Treatise on Physics, 9th ed. (1858), *1*, p. 233.—Comptes Rendus, *3* (1836), p. 782.

Ed. Becquerel.—C. R., *57* (1863), pp. 855, 902, 955.

Sainte-Claire-Deville and Troost.—C. R., *90* (1880), pp. 727, 773; *45* (1857), p. 821; *49* (1859), p. 239; *56*, p. 977; *57* (1863), pp. 894, 935; *98* (1884), p. 1427; *69* (1864), p. 162.—Ann. Chim. et Phys. (3), *58* (1860), p. 257.—Répert. Chim. Appl. (1863), p. 326.

Violle.—Specific heat of platinum. C. R., *85* (1877), p. 543.—Specific heat of palladium. C. R., *87* (1878), p. 98; *89* (1879), p. 702.— Boiling-point of zinc. C. R., *94* (1882), p. 721.

Barus.—Bull. U. S. Geological Survey, No. 54 (1889); Phil. Mag. (5), *34* (1892), p. 1.—Report on Pyrometry, Congress at Paris, 1900.

Regnault.—Account of his experiments, *1*, p. 168 (Paris 1847); Mém. de l'Institut, *21* (1847), pp. 91, 110; Ann. Chim. et Phys. (3), *68* (1861), p. 89.

Holborn and Wien.—Bull. de la Soc. pour l'encouragement (5), *1* (1896), p. 1012; Wied. Ann., *47* (1892), p. 107; *46* (1895), p. 360.—Zeits. für Instrum. (1892), p. 257.

Crafts and Meier.—Vapor density of iodine. C. R., *90* (1880), p. 690.

Jolly.—Pogg. Ann., Jubelband (1874), p. 97.

Randall.—Permeability of platinum. Bull. Soc. Chim., *21* (1898), p. 682.

Mallard and Le Chatelier.—Ann. des Mines, *4* (1884), p. 276.

J. R. Erskine Murray.—On a new form of constant-volume air-thermometer, Edinburgh Proc., *21* (1896-97), p. 299, and Journ. Phys. Chem., *1* (1897), p. 714.

J. Rosse-Innes.—The thermodynamic correction for an air-thermometer, etc. Nature, *58* (1898), p. 77.—Phil. Mag. (5), *45*, (1898), p. 227; *50* (1900), p. 251.—Proc. Phys. Soc. London, *16* (1), (1898), p. 26.

Chappuis.—Phil. Mag. (5), *50* (1900), p. 433.—Report for Paris Congress, 1900.—Jour. de Phys., Jan. 1901, p. 20.

D. Berthelot.—On a new method of temperature measurement. C. R., *120* (1895), p. 831.

Holborn and Day.—Wied. Ann., *68* (1899), p. 817, and Am. Jour. (4), *8* (1899), p. 165; Zeitschr. Instrum., May 1900.—Am. Jour. (4), *10* (1900), p. 171, and Drude's Ann., *2* (1900), p. 505.

Chappuis and Harker.—Trav. et Mém. du Bureau Int. des Poids, etc., 1900; Phil. Trans., 1900.

Callendar.—Phil. Mag., *48* (1899), p. 519.

CALORIMETRIC PYROMETER.

Violle.—Boiling and fusing points. C. R., *89* (1879), p. 702.

Le Chatelier.—Sixteenth Congress of the Société technique de l'industrie du gaz (June 1889).

Euchêne.—Thermal relations in the distillation of oil. (Monograph.)

Berthelot.—Calorimetry.   Ann. Chim. et Phys., 4th Series, *20*, p. 109; 5th Series, *5*, p. 5; 5th Series, *10*, pp. 433, 447; 5th Series, *12*, p. 550.

ELECTRICAL-RESISTANCE PYROMETER.

W. Siemens.—Proc. Royal Soc., *19* (1871), p. 351.—Bakerian Lecture, 1871.—Transactions of the Society of Telegraph Engineers, 1879.—British Association, 1874, p. 242.
Müller.—Pogg. Ann., *103* (1858), p. 176.
Benoit.—C. R., *76* (1873), p. 342.
Callendar.—Phil. Trans. of R. S., *178* (1888), pp. 160-230; Proc. Roy. Soc. London, *41* (1886), p. 231, and Phil. Trans., 1887.—Phil. Trans. (1892), p. 119 (with *Griffiths*).—Platinum pyrometers.   Iron and Steel Institute, May 1892.—Phil. Mag., *32* (1891), p. 104; *33* (1892), p. 220.—Proposals for a standard scale of temperatures.   B. A. Report, 1899; Phil. Mag., *47* (1899), pp. 191, 519, is a résumé of the question.
Heycock and Neville.—Determination of high temperatures.   J. of Chem. Society, *68* (1895), pp. 160, 1024.
Barus.—Amer. Jour. (3), *36* (1888), p. 427.
Holborn and Wien.—Ann. der Phys. u. Chem., *47* (1892), p. 107; *56* (1895), p. 360.—Bull. de la Soc. d'encouragement, 5th Series, *1* (1896), p. 1012.
Chappuis and Harker.—A comparison of platinum and gas-thermometers made at the B. Int. des Poids et Mesures.   B. A. Report, 1899.—Trav. et Mém. du Bureau Int. des Poids et Mesures, 1900; Phil. Trans., 1900; Jour. de Phys., Jan. 1901.
Appleyard.—Phil. Mag. (5), *41* (1896), p. 62.
Dickson.—Phil. Mag. (5), *44* (1897), p. 445; *45* (1898), p. 525.
Wade.—Wied. Beibl., *23* (1899), p. 963; Proc. Cambr. Soc., *9* (1898), p. 526.
Chrustchow and Sitnikow.—Tagebl. d. russ. Naturf. Vers. zu Kiew (1898), p. 438.

THERMOELECTRIC PYROMETER.

Becquerel.—Ann. Chim. et Phys., 2d Series, *31* (1826), p. 371.
Pouillet.—Traité de Physique, 4th Ed., *2*, p. 684.—C. R., *3*, p. 786.
Ed. Becquerel.—Annales du Conservatoire, *4* (1864), p. 597.—C. R.,

55 (1862), p. 826.—Ann. de Chim. et de Phys., 3d Series, *68* (1863), p. 49.

Tait.—Trans. Roy. Soc. Edinb., *27* (1872-73), p. 125.

Regnault.—Account of investigations on heat-engines, *1*, p. 240.— C. R., *21* (1847), p. 240.

Knott and MacGregor.—Trans. Roy. Soc. Edinb., *28* (1876-77), p. 321.

Le Chatelier.—Thermoelectric pyrometer. C. R., *102* (1886), p. 819.—Journal de Phys., 2d Series, *6*, Jan. 1887.—Genie civil, March 5, 1887.—16th Congress of the Société technique de l'industrie du gaz, June 1889.—Bull. de la Société de l'encouragement (1892).—Bull. Soc. Chim. Paris, *47* (1887), p. 42.

Barus.—Washington, 1889, Bull. of the U. S. Geological Survey, No. 54, No. 103 (No. 54 contains a very complete historical account of the whole subject of pyrometry).—Phil. Mag. (5), *34* (1892), p. 376.—Am. Jour., *36* (1888), p. 427; *47* (3), (1894), p. 366; *48*, p. 336.

Holborn and Wien.—Wied. Ann., *47* (1892), p. 107; *56* (1895), p. 360.—Zeit. des Vereines deutscher Ingenieure, *41* (1896), p. 226.—Stahl und Eisen, *16*, p. 840.

Roberts-Austen.—Recent progress in pyrometry. Trans. Am. Institute of Mining Engineers, 1893.
     (*See also* Recording Pyrometers.)

Quincke.—Ceramic insulators for very high temperatures. Zeit. der Vereins deut. Ingenieure, *40*, p. 101.

Struthers.—Thermoelectric pyrometer of Le Chatelier. School of Mines Quarterly, New York, *12*.

E. Damour.—Bull. de l'Assoc. amicale des anciens élèves de l'Ecole des Mines (March 1889).

H. Howe.—Pyrometric data. Engineering and Mining Journal, *50* (1890), p. 426.

Holborn and Day.—On the melting-point of gold. Drude's Ann., *4* (1), (1901), p. 99; Am. Jour. of Sci., *11*, Feb. 1901, p. 145.— On the thermoelectric properties of certain metals. Sitz. Berl. Akad. (1899), p. 69; Am. Jour. of Sci. (4), *8* (1899), p. 303; Mitth. Phys.-tech. Reichsanst., *37* (1899).

Stansfield.—Phil. Mag. (5), *46* (1898), p. 59.

Holman.—Phil. Mag., *41* (1896), p. 465; Proc. Am. Acad., *31*, p. 234.

Holman, Lawrence and Barr.—Phil. Mag., *42* (1896), p. 37; Proc. Am. Acad., *31*, p. 218.

Schoentjes.—Arch. de Phys. (4), *5* (1898), p. 136.

Noll.—Thermoelectricity of chemically pure metals. Wied. Ann., 1894, p. 874.

Steinmann.—Thermoelectricity of certain alloys. C. R., *130* (1900), p. 1300; *131* (1900), p. 34.

Belloc.—Thermoelectricity of steels. C. R., *131* (1900), p. 336.

HEAT-RADIATION PYROMETER.

Violle.—Solar radiation. Ann. Chim. et Phys., 5th Series, *20* (1877), p. 289.—Jour. de Phys. (1876), p. 277.

Rosetti.—Ann. Chim. et Phys., *17* (1879), p. 177.—Phil. Mag., *8* (1879), p. 324.

Deprez and d'Arsonval.—Société de Physique, Feb. 5, 1886.

Boys.—Radiomicrometer. Phil. Trans., *180* (1887), p. 159.

Wilson and Gray.—Temperature of the Sun. Phil. Trans., *185* (1894), p. 361.

Langley.—Bolometer. Am. Jour. of Science, *21* (1881), p. 187; *31*, (1886), p. 1; *32* (1886), p. 90; (4), *5* (1898), p. 241.—Jour. de Phys., *9*, p. 59.

Terreschin.—Diss. St. Petersburg, 1898. Jour. Russ. phys.-chem. Ges., *29* (1897), pp. 22, 169, 277.

Lummer and Kurlbaum.—Verh. phys. Ges., *17* (1898), p. 106.

Petravel.—Proc. Roy. Soc., *63* (1898), p. 403.

Abbot.—Bolometer. Astrophys. Jour., *8* (1898), p. 250.

Belloc.—Bolometer errors. L'éclair. elec. (5), *15* (1898), p. 383.

LUMINOUS-RADIATION PYROMETER.

Kirchoff.—Ann. Chim. et Phys., *59* (1860), p. 124.

Ed. Becquerel.—Optical measurement of temperatures. C. R., *55* (1863), p. 826.—Ann. Chim. et Phys., *68* (1863), p. 49.

Violle.—Radiation from platinum. C. R., *88* (1879), p. 171; *91* (1881), pp. 866, 1204.

Crova.—C. R., *87*, pp. 322, 329; *90*, p. 252; *92*, pp. 36, 707; *114*, p. 941; *126*, p. 1394.

Le Chatelier.—Optical pyrometer. C. R., *114* (1892), p. 214; J. de Phys., 3d Series, *1* (1892); Industrie électrique, April 1892.—On the temperature of the sun. C. R., *114* (1892), p. 737.—On the temperatures of industrial furnaces. C. R., *114* (1892), p. 470.

Stefan.—Wien. Ber., *179* (1879), p. 391.

Boltzmann.—Wied. Ann., *22* (1884).

Paschen.—Wied. Ann., *60* (1897); Astrophys. Jour., *10* (1899), p. 40; *11* (1900), p. 288.

C. E. Mendenhall and Saunders.—Astrophys. Jour., *13* (1901), p. 25.

Lummer.—Report Phys. Congress, Paris, 1900: Radiation from black bodies.

Lummer and Pringsheim.—Wied. Ann., *63* (1897), p. 395.—Verh. d. Deutsch. Phys. Ges., *1* (1899), pp. 1, 12; *2*, No. 5 (1900).

Planck.—Drude's Ann., *1*, Nos. 1, 4 (1900).

Wien.—Ber. der Berl. Akad., *6* (1893).—Report Phys. Congress, Paris, 1900: Laws of Radiation.

Kurlbaum.—Wied. Ann. *67* (1899), p. 846.

CONTRACTION PYROMETER.

Wedgwood.—Phil. Trans., *72* (1782), p. 305; *74* (1784), p. 358.

Guyton and Morveau.—Ann. Chim. et Phys., 1st Series, *46* (1803), p. 276; *73* (1810), p. 254; *74* (1810), pp. 18, 129; *90* (1814), pp. 113, 225.

J. Joly.—The melodometer. Proc. Roy. Irish Academy, 3d Serie⁻ 2 (1891), p. 38.

Ramsay and Eumorfopoulos.—Phil. Mag., *41* (1896), p. 360.

FUSIBLE-CONE PYROMETER.

Lauth and Vogt.—Pyrometric measurements. Bull. Soc. Chim. *46* (1886), p. 786.

Seger.—Thorindustrie Zeitung, 1885, p. 121; 1886, pp. 135, 229.

RECORDING PYROMETERS.

Le Chatelier.—Study of clays. C. R., *104* (1887), p. 1443.

Roberts-Austen.—First Report of the Alloys Research Committee, Proc. Inst. Mech. Engrs. (1891), p. 543.—Nature, *45* (1892).— B. A. Report (1891).—Jour. of Soc. of Chem. Industry, *46* (1896), p. 1.—Proc. Inst. Mech. Eng. (1895), p. 269; (1897), pp. 67, 243.—Proc. Roy. Soc., *49* (1891), p. 347.

G. Charpy.—Study of the tempering of steel. Bull. de la Soc. d'encouragement, 4th Series, *10* (1895), p. 666.

Callendar.—Platinum recording pyrometer. Engineering, May 26, (1899), p. 675.

Stansfield.—Phil. Mag. (5), *46* (1898), p. 59; Phys. Soc. London, *16* (2), (1898), p. 103.

Bristol.—Air-pyrometer. Eng. News, Dec. 13, 1900.

FUSING AND BOILING POINTS.

FUSION.

Prinsep.—Ann. Chim. et Phys., 2d Series, *41* (1829), p. 247.

Lauth.—Bull. Soc. Chim. Paris, *46* (1886), p. 786.

E. Becquerel.—Ann. Chim. et Phys., 3d Series, *68* (1863), p. 497.

Violle.—C. R., *85* (1877), p. 543; *87* (1878), p. 981; *89* (1879), p. 702.

Holborn and Wien.—Wied. Ann., *47* (1892), p. 107; *56* (1895), p. 360; also Zeits. für Instrumentenk. (1892), p. 257.

Holborn and Day.—Drude's Ann., *4*, 1 (1901), p. 99, and Am. Jour. of Sci., *11* (1901), p. 145.—Wied. Ann., *68* (1899), p. 817, and Am. Jour. of Sci. (4), *8* (1899), p. 165.

Ehrhardt and Schertel.—Jahrls. für das Berg. und Hüttenw. im K. Sachsen (1879), p. 154.

Ledeboer.—Wied. Beib., *5* (1881), p. 650.

Van der Weyde.—1879, *see* Carnelley's Tables.

Callendar.—Phil. Mag., 5th Series, *47* (1899), p. 191; *48*, p. 519.

Curie.—Ann. de Chim. et de Phys., 5th Series, *5* (1895).

Barus.—Bull. 54, U. S. Geological Survey (1889), and Behandlung u. Messung hoher Temp. Leipzig (1892); Am. Jour. of Sci., 3d Series, *48* (1894), p. 332.

Berthelot.—C. R., *126*, Feb. 1898.

Le Chatelier.—C. R., *114* (1892), p. 470.

V. Meyer, Riddle and Lamb.—Chem. Ber., *27* (1894), p. 3129. (Salts.)

Moldenke.—Zeits. für Instrumentenk., *19* (1898), p. 153. (Iron and Steel.)

Cusack.—Proc. Roy. Irish Acad., 3d Series, *4* (1899), p. 399.

Landolt and Börnstein.—Phys. Chem. Tabellen, Berlin, 1894.

Carnelley.—Melting and Boiling Point Tables, London, 1885.

Holman, Lawrence and Barr.—Phil. Mag. (5), *42* (1896), p. 37, and Proc. Am. Acad., *31*, p. 218.

Heycock and Neville.—Phil. Trans., *189,* p. 25; Jour. Chem. Soc., 71 (1897), p. 333; Nature, *55* (1897), p. 502; Chem. News, *75* (1897), p. 160.

EBULLITION.

Barus.—L. C. (under Fusion), and Am. Jour. (5), *48* (1894), p. 332.

Troost.—C. R., *94* (1882), p. 788; *94* (1882), p. 1508; *95* (1882), p. 30.

Le Chatelier.—C. R., *121* (1895), p. 323. (*See also under* Thermo-electric Pyrometer.)

Berthelot.—Séances de la soc. de physique, Paris, Feb. 1898, and Bull. du Muséum, No. 6 (1898), p. 301.

Callendar and Griffiths.—Proc. Roy. Soc. London, *49* (1891), p. 56.

Chappuis and Harker.—Travaux et Mem. du Bureau Int. des Poids et des Mesures, *12,* 1900; Phil. Trans., 1900.

Preyer and V. Meyer.—Zeits. für Anorg. Chem., 2 (1892), p. 1; Berl. Ber., *25* (1892), p. 622.

S. Young.—Trans. Chem. Soc. (1891), p. 629.

MacCrae.—Wied. Ann., *55* (1895), p. 95.

Callendar.—Phil. Mag. (5), *48* (1899), p. 519. (Fusion also.)

VARIOUS SUBJECTS.

Holborn and Day.—On the expansion of certain metals at high temperatures. Drude's Ann., *4,* 1 (1901), p. 104.

Deville and Troost.—Expansion of porcelain. C. R., *57* (1863), p. 897.

T. G. Bedford.—On the expansion of porcelain with rise of temperature. B. A. Report, 1899.

Le Chatelier.—Dilatation of iron, steel, copper alloys, etc. C. R., *128* (1899), p. 1444; *129,* p. 331; also C. R., *107* (1888), p. 862; *108* (1896), p. 1046; *111* (1890), p. 123.—Specific heat of carbon. C. R., *116* (1893), p. 1051; Soc. Franc. de Phys., No. 107 (1898), 3.

Barus.—Bull. of U. S. Geological Survey, No. 54, 1889. (Pyrometry.) Report on the progress of pyrometry to the Paris Congress, 1900. (This is the latest and best summary of pyrometric methods to date.)—Viscosity and temperature. Wied. Ann.,

96 (1899), p. 358; and *Callendar,* Nature, *49* (1899), p. 494.—Long-range temperature and pressure variables in physics. Nature, *56* (1897), p. 528.

Baly and Chorley.—Liquid-expansion pyrometer. Berl. Ber., *27* (1894), p. 470.

Dufour.—Tin in quartz-pyrometer. C. R., *180* (1900), p. 775.

Berthelot.—Interference method of high-temperature measurements. C. R., *120* (1895), p. 831; Jour. de Phys. (3), *4* (1895), p. 357; C. R., Jan. 1898; applications in C. R., Feb. 1898.

Moissan.—Le four électrique, Paris, 1898.

Fliegner.—Specific heat of gases. Wied. Beibl., *23* (1899), p. 964.

Töpler.—Pressure-level apparatus. Wied. Ann., *56* (1895), p. 609; *57* (1896), p. 311.

Quincke.—An acoustic thermometer for high and low temperatures. Wied. Ann., *63* (1897), p. 66.

K. Scheel.—Ueber Fernthermometer. Verlag v. C. Marhold, Halle, 1898. 48 pp.

Heitmann.—Ueber einen neuen Temperatur-Fernmessapparat von Hartmann und Braun. E. T. Z., *19* (1898), p. 355.

Chree.—Recent work in thermometry. Nature, *58* (1898), p. 304.

Lémeray.—On a relation between the dilation and the fusing-points of simple metals. C. R., *131* (1900), p. 1291.

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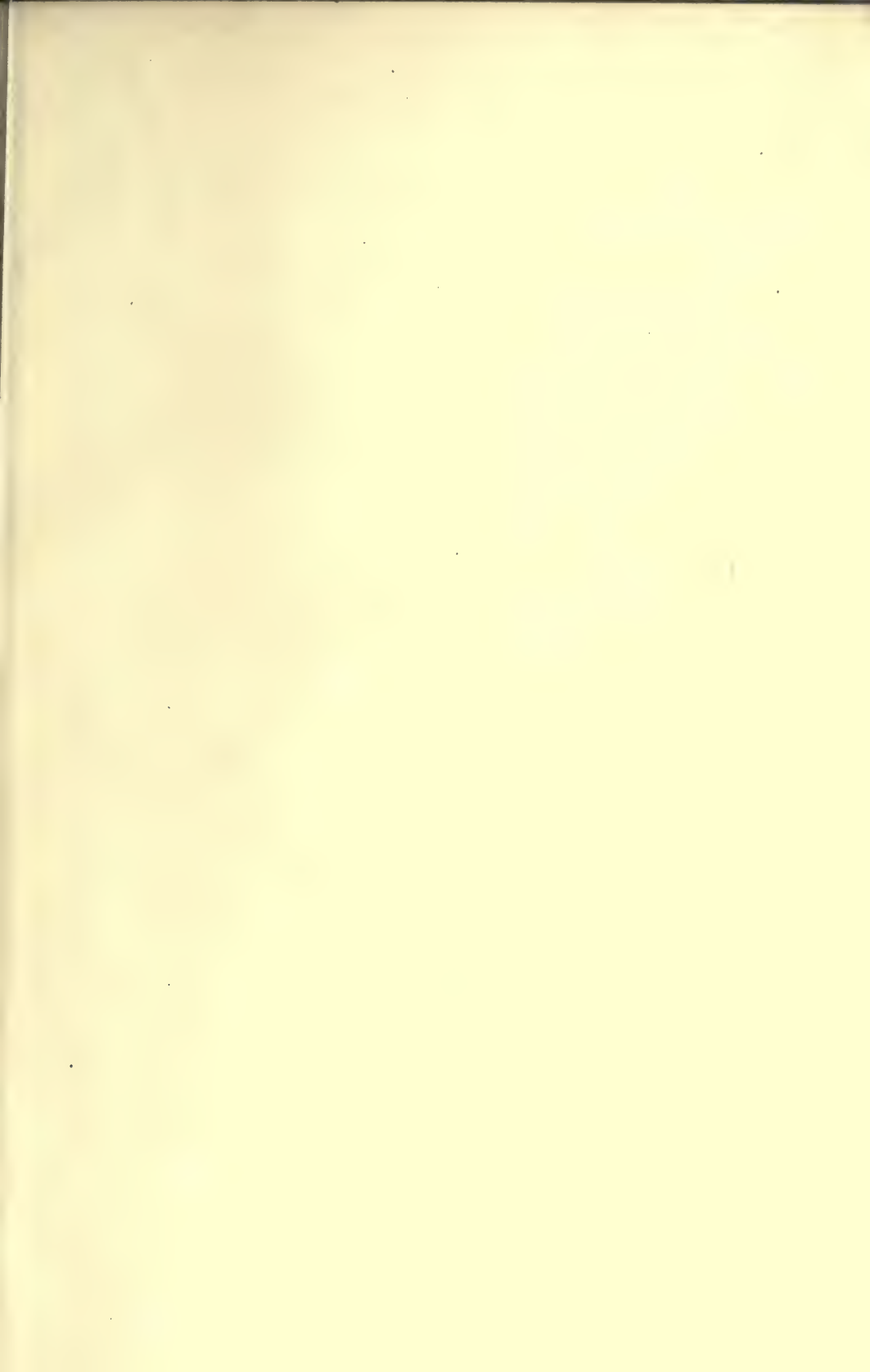|	
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